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THESIS

| FOUNDATIONS OF THE INTELLIGENCE MODULE
OF THE AIRLAND RESEARCH MODEL
(ALARM)

by

Gaylon L. Smith

September 1986

Thesis Advisor: Samuel H. Parry

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(ALARM)

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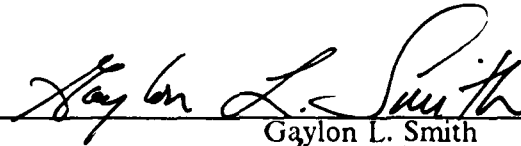B.A., Saint Louis University, 1972

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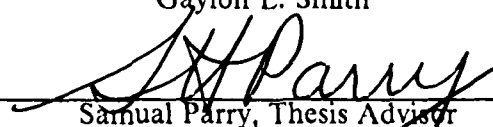
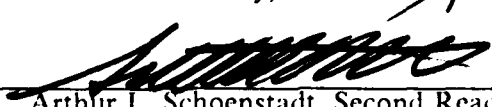MASTER OF SCIENCE IN OPERATIONS RESEARCH

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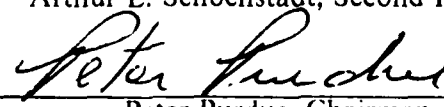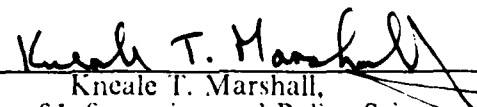Gaylon L. Smith

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ABSTRACT

This thesis lays the foundation for the Intelligence Module of the AIRLAND RESEARCH MODEL (ALARM). It examines the relationship between the Intelligence Module and the other modules of ALARM. Specifically it develops the structure of the Intelligence Module to include the flow of combat information from other modules, the fusion of combat information into tactical intelligence and the subsequent dissemination of that intelligence. Additionally it proposes a Lanchester-type formulation for target acquisition and presents a methodology to estimate the required coefficients from the output of a high resolution combat simulation.

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I. INTRODUCTION

A. PURPOSE AND ORGANIZATION OF THE THESIS

This thesis lays the foundation for the Intelligence Module of the AIRLAND RESEARCH MODEL (ALARM). It examines the relationship between the Intelligence Module and the other modules of ALARM. Specifically it develops the the structure of the Intelligence Module to include the flow of combat information from other modules, the fusion of combat information into tactical intelligence and the subsequent dissemination of that intelligence. Additionally it proposes a Lanchester-type formulation for target acquisition and presents a methodology to estimate the required coefficients from the output of a high resolution combat simulation. The thesis is organized as follows:

1. Review of the AirLand Battlefield and the AIRLAND RESEARCH MODEL (ALARM).
2. Overview of the current tactical intelligence system of the U.S. Army.
3. Development of the Intelligence Module of ALARM.
4. Discussion of the functions of the Combat Intelligence Processor and methodologies for implementing them.
5. Review of the Glimpse and Continuous-search models of target acquisition.
6. Modeling target acquisition using a Lanchester-type formulation.
7. Estimation of Lanchesterian coefficients using maximum likelihood estimators.
8. Illustration of the inter-relationships between the Intelligence, Execution and Planning Modules of ALARM using a worked example.
9. Discussion of areas requiring additional research/study.

The thesis is concerned with modeling the tactical intelligence system of the United States ground forces at the corps level and below. It concentrates on U.S. Army forces employed in the European Theater against Soviet forces. Models of the Soviet tactical intelligence system will not be explored. However, it is anticipated that many of the basic constructs developed in this thesis can be applied with a minimum of modification in future studies. Similarly the acquisition of combat information by U.S. Air Force assets will be addressed in the research being done on the Air Force

sub-module of ALARM. Finally, although an important source of combat information and intelligence, echelons above corps are not specifically addressed in this thesis.

Before continuing with the development of the Intelligence Module the characteristics of the AirLand Battlefield are examined and the structure of the AIRLAND RESEARCH MODEL, as currently envisioned, is reviewed.

B. CHARACTERISTICS OF THE AIRLAND BATTLEFIELD

The U.S. Army Field Manual 100-5 [Ref. 1:pp. 1-1,1-2] lists eight characteristics that will distinguish the airland battlefield:

1. Nonlinear Maneuver Battles - The U.S. Army will face enemy forces which are highly mechanized and possess very sophisticated and lethal weapon systems. The enemy forces will integrate armored ground forces with air power and the potential use of nuclear/chemical weapons. Both sides will be able to rapidly mass troops and fires in order to achieve penetrations. As a result distinct lines of battle, which have characterized past wars and many current models , will be the exception.

2. Lethal Systems - Both the U.S. and enemy forces will possess weapons of high quality and lethality. The coordinated use of air and ground precision guided munitions will allow the concentration of combat power at critical points on the battlefield.

3. Sensors and Communications. - The wide-spread availability of surveillance and target acquisition sensors, coupled with an extensive communications system, will allow rapid dissemination of combat information and tactical intelligence. This will affect both the range and scope of the battle.

4. Nuclear and Chemical Warfare - The potential use of nuclear and / or chemical weapons will drastically alter the battlefield. The threat of their use will preclude the massing of troops, except for short periods. It is possible that tactical nuclear weapons will come to dominate the battle and relatively small maneuver forces will be used to exploit their effects. The tempo of the battlefield will increase while the duration of specific battles will decrease.

5. Command and Control - Effective command and control will be a decisive factor in future battles. Ironically, the vulnerability of communication systems to electronic countermeasures may significantly degrade the commanders ability to communicate with, and subsequently control, his forces at critical junctures in the battle. Command and control facilities will be specifically targeted.

6. Air Systems - The use of helicopters and tactical air power will extend the depth of the battle. The effective use of air defense will become an important issue in future battles.

7. Austere Support - Future battles will be fought at the end of long and vulnerable supply lines. The ability of both sides to strike deep will hamper resupply to the fighting forces. Additionally the nonlinear, maneuver oriented battlefield will preclude the stockpiling of supplies in any great quantities.

8. Rear Area Combat - Support systems in the rear area will be the focus of intense attacks intended to disrupt the flow of crucial supplies, replacements and information. The goal will be to reduce the effectiveness of the fighting forces by denying them needed support. Additionally, maneuver forces will be siphoned from the main battle area in order to provide protection to rear area support facilities.

These characteristics describe a battlefield which is potentially very different from those of the recent past. New operational and tactical doctrines have been and are in the process of being developed. These new doctrinal concepts are being explored using field training exercises (FTX's), command-post exercises (CPX's), wargames and computer simulations. Many of the combat models (computer simulations) which are currently in use are modifications of dated models. ALARM is an attempt to explore new methodology based on what is believed to the true nature of the modern battlefield.

C. THE AIRLAND RESEARCH MODEL (ALARM)

ALARM will be used initially to model the interdiction battle at the corps level and below. The interdiction battle is the foundation of the U.S. Army's AirLand Battle doctrine. Three primary purposes have been identified for ALARM [Ref. 2]:

1. The development of modeling methodology appropriate for the very large scale but sparsely populated rear areas involved in the (non-FLOT) interdiction battle, and for the command and control of the AirLand Battle force.

2. The application of these methodologies in the construction of a simulation/wargaming model initially focusing on two-sided interdiction.

3. The eventual use of the model to perform research on the conduct of the total AirLand Battle.

The goal of the development effort is to produce a systemic model which will allow for a detailed audit trail by which an analysis of the cause and effect relationships can be conducted. ALARM has the following unique features:

1. Systemic architecture which allows the model to conduct the simulation without the requirement for human intervention at critical decision points.

2. Rule-based decision systems in which the command and control (C^2) functions are automated, along with related processes.

3. A Network representation which uses a generalized network methodology and multidimensional coordinate systems to represent terrain, transportation and communication interconnections, and command and control relationships.

4. A Generalized Value System (GVS) which is the base concept for the future state decision making featured in the model. The GVS assigns an initial value to a combat unit based on the availability of weapons, personnel and supplies. This initial value is then adjusted (discounted) to reflect the time delay that may be required before the unit is in position to accomplish its assigned mission. The initial values of logistic/support units and other battlefield entities are determined primarily from their ability to increase the value of combat units. Extensive research on the GVS has been conducted by Kilmer. [Ref. 3]

ALARM is a testbed for examining methodology; it is not a production model. The proposed computer model of ALARM, as currently conceived, has three major components: a Planning Module, an Execution Module and an Intelligence Module. These modules are currently being developed. Figure 1.1 displays a simplified diagram of the relationship between the three modules. The Planning Module includes the decision algorithms and consists of several submodules. Figure 1.2 shows a division planning sub-module in more detail. There is a planning sub-module for each hierarchical level of the task force organization (battalion through corps), to include, as required, associated sub-modules for indirect fire, engineering, logistics, U.S. Army aviation, maintenance etc.

The planning sub-modules develop detailed plans for execution using decision algorithms and available information from the Execution Module. Figure 1.3 displays the stages in a planning sub-module for a single U.S. unit and the interaction between the planning sub-module and the Execution Module. Briefly, the unit receives the commander's guidance, which usually consists of the higher headquarters plan for the

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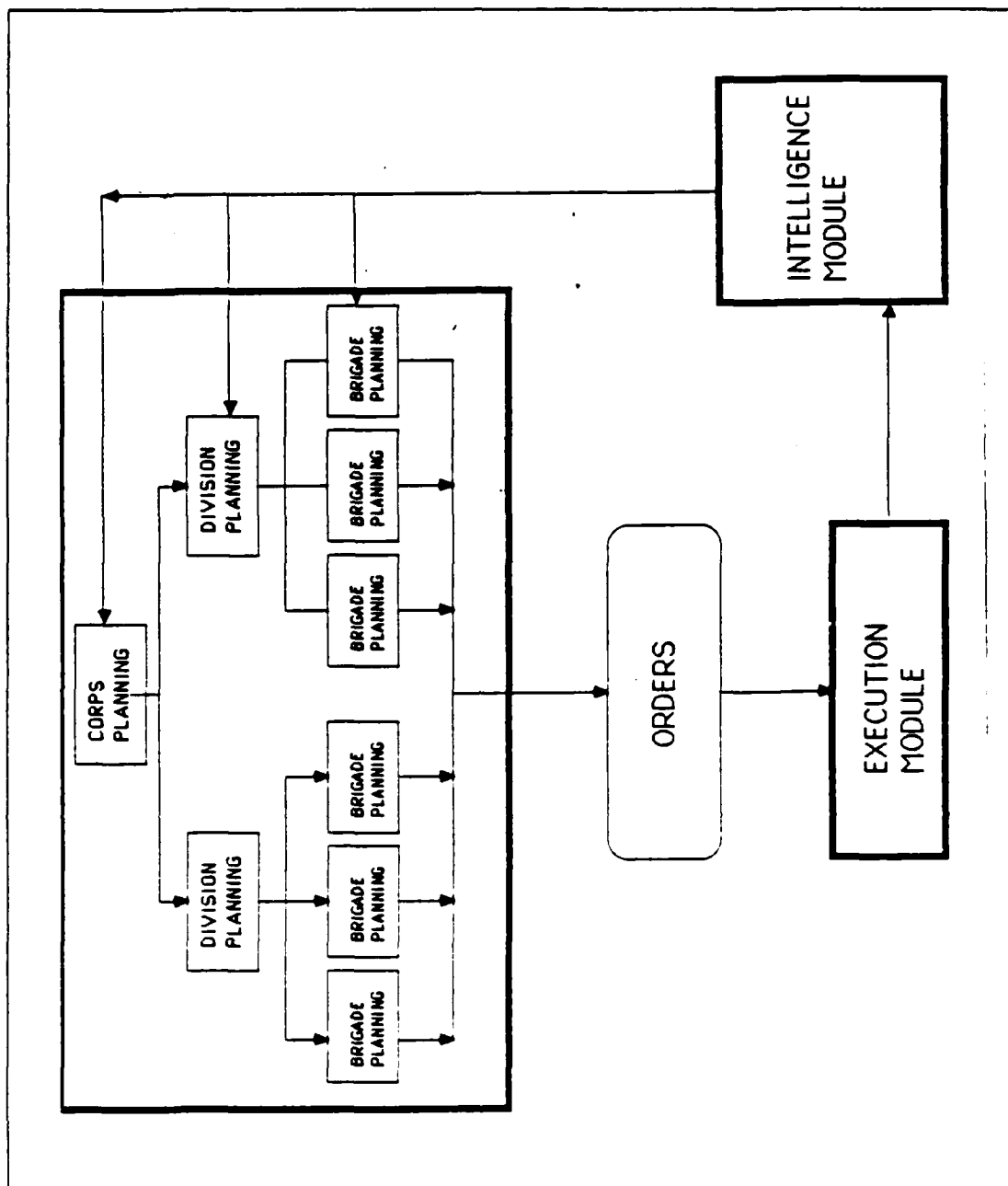
Figure 1.1   Modular Structure of ALARM.

operation and some specific directives for its implementation. Courses of action are developed and feasibility checks conducted. A detailed plan of action is then prepared which is sent to the Execution Module. In the Execution Module the plan parameters
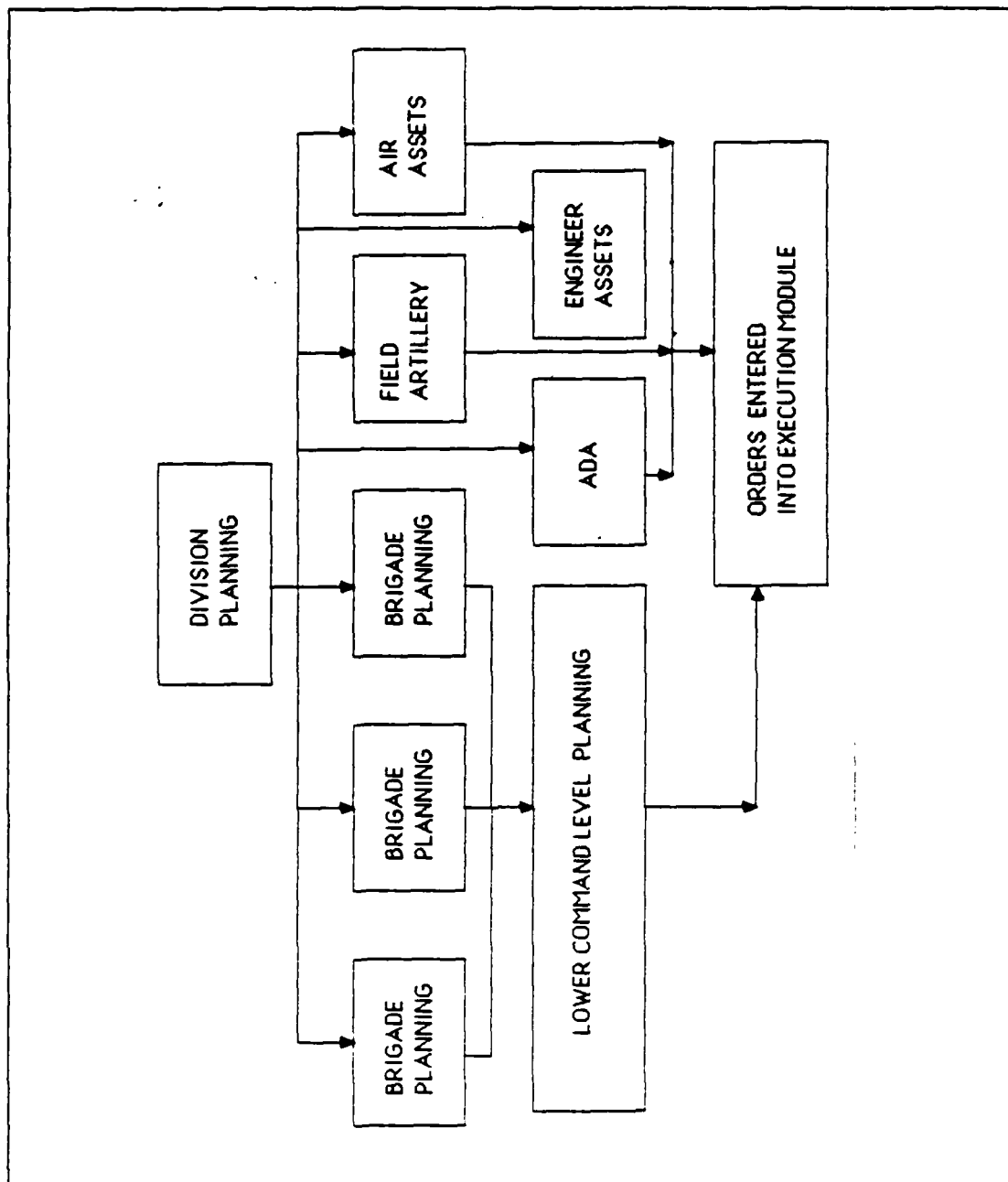
Figure 1.2   Division Planning Sub-Module.

are initially checked to insure that they conform to the commanders guidance. During the execution, decision threshold parameters are monitored. Violation of a decision threshold parameter may cause the planning cycle to be re-entered and the plan

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modified. Current research is concentrating on developing the Planning Module, the planning sub-modules which comprise it, and the inter-relationships between the various sub-modules.
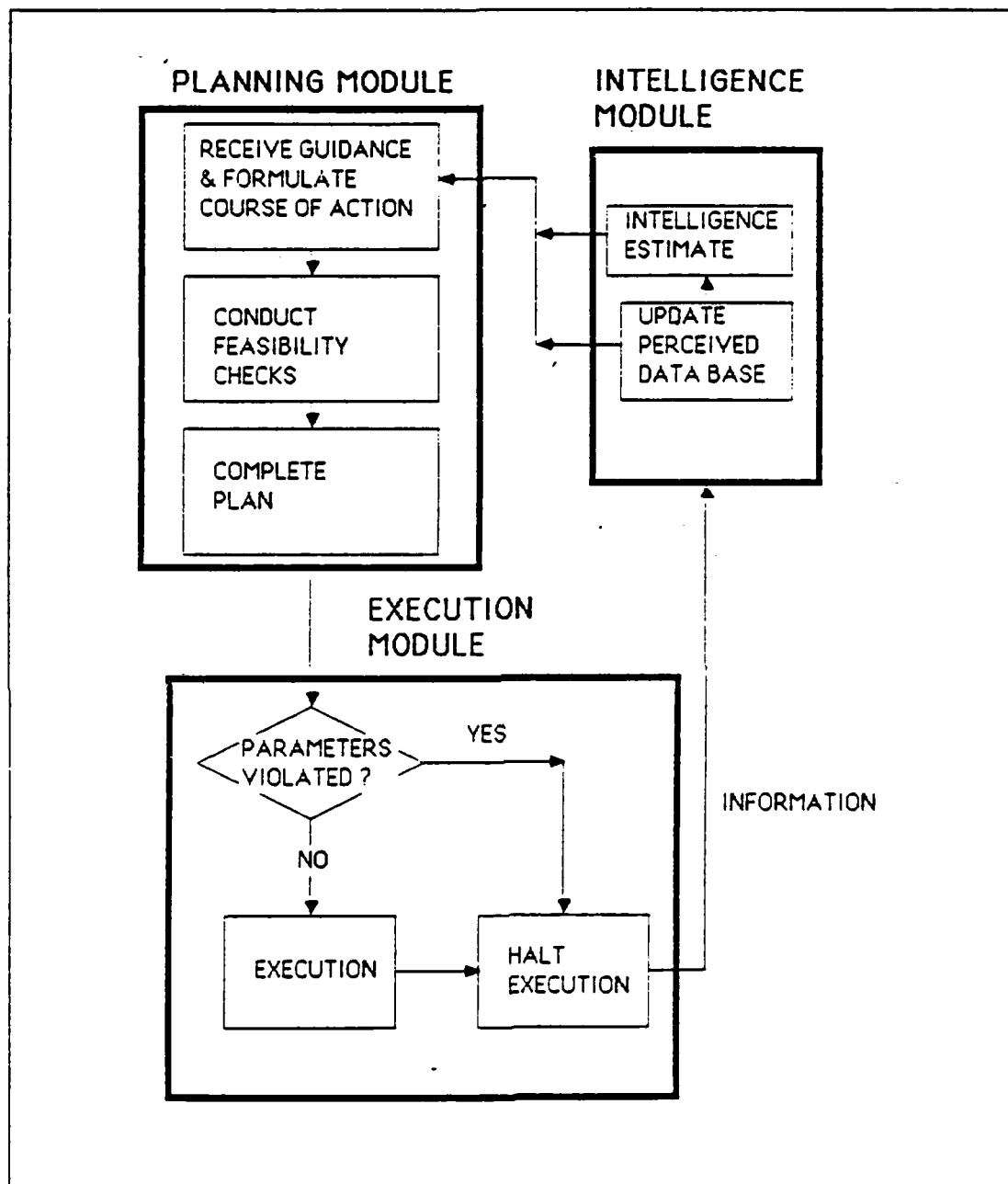
Figure 1.3   Unit Planning.

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It is apparent that the Intelligence Module plays a key role in the interaction between the Planning Module and the Execution Module. The Intelligence Module receives raw data (combat information) concerning enemy forces and other model entities from the Execution Module. It then must separate this information and pass it along to the appropriate level in the Planning Module. For instance, during the execution of a division operation it must determine what information should be made available to each battalion and brigade planning sub-module (to include their related support planning sub-modules). This availability of information may be a function of the unit's location on the battlefield, task force organization, and unit composition and strength. One important issue concerns whether this information should represent the "ground truth" or some perceived truth. If the data is to be transformed, how should this be accomplished ? This issue is addressed later in the thesis.

A second function of the Intelligence Module, which is not apparent from the figures, is the preparation of an intelligence estimate. This intelligence estimate is an integral part of the planning module. Thus each hierarchical level which possesses an intelligence analysis capability has an intelligence sub-module associated with its planning sub-module. These intelligence sub-modules are responsible for the fusion of existing intelligence and combat information into a intelligence estimate which can be used by the planning sub-module. The intelligence system and the development of a model is addressed next.

II. DEVELOPMENT OF AN INTELLIGENCE MODEL

A. AN OVERVIEW OF THE TACTICAL INTELLIGENCE SYSTEM

The AirLand Battle concept of interdiction, or the deep battle, is extremely dependent upon accurate and timely information about enemy units and battlefield conditions. The tactical intelligence system is responsible for the collection and evaluation of information the and dissemination of intelligence to the tactical decision maker. First it is necessary to clarify the distinction between information, combat information and tactical intelligence.

- Def: INFORMATION - unevaluated material including that derived from observations, communications, reports, rumors, imagery or any other source. The information may or may not be true, accurate and/ or even pertinent. Information can also be negative in the sense that an event may have not occurred, or that an item of interest is absent from the battlefield.

- Def: COMBAT INFORMATION - information upon which minimal verification and validation has been conducted. It is characterized by being readily exploitable, near real-time delivery from source to user, and used immediately for tactical execution and fire support.

- Def: TACTICAL INTELLIGENCE - the product resulting from the collection, evaluation and interpretation of information. The goal of tactical intelligence is to minimize the uncertainty concerning the enemy's objectives, capabilities and battlefield conditions which may effect the accomplishment of the mission. It is characterized as all-source, complex and a result of detailed analysis. It is delivered in hours, and used for planning.

The tactical intelligence system focuses the intelligence effort by delimiting collection and evaluation responsibilities for each subordinate unit and by setting priorities for information upon which collection is to be concentrated.

- Def: ESSENTIAL ELEMENTS OF INFORMATION (EEI) - those critical items of information about the enemy and battlefield needed by the commander to assist him in reaching a logical decision. EEI are often time sensitive.

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EEI requirements are generally provided to the unit from its superior headquarters. Additional EEI, which support its specific mission, may be developed by the unit itself. Collection efforts are centered on satisfying these EEI requirements.

To further enhance the collection effort each tactical unit is assigned a geographical area for intelligence operations. This geographical area is subdivided into an Area of Influence and an Area of Interest.

- Def: AREA OF INFLUENCE - that portion of the assigned area of operation in which the commander can directly affect the course of the battle using his own organic and supporting assets.

The actual area will vary in size depending upon the terrain, enemy capability and disposition, and the unit's ability to react to enemy actions. The area is specified in terms of time. Normally, a commander will possess the means for monitoring and collecting combat information within the area of influence. Table 1 displays typical area of influence assignments for various levels of command.

TABLE 1

TYPICAL AREAS OF INFLUENCE

Level of command	Time Beyond FLOT or Attack Objectives
Battalion	up to 3 hours
Brigade	up to 12 hours
Division	up to 24 hours
Corps	up to 72 hours

In addition to an area of influence each unit has an area of interest.

- Def: AREA OF INTEREST - includes the area of influence and extends beyond and laterally to those areas in which enemy units or battlefield conditions are capable of affecting a unit's mission in the near future.

Again the area of interest is specified in terms of time and assigned after considering the terrain, enemy and the unit's status. Unlike the area of influence a unit does not normally have the capability of monitoring its area of interest. Rather, the

unit receives information about the area of interest primarily from higher and adjacent units. Table 2 displays typical area of interest assignments for various levels of command.

TABLE 2

TYPICAL AREAS OF INTEREST

Level of Command	Time Beyond FLOT or Attack Objectives
Battalion	up to 12 hours
Brigade	up to 24 hours
Division	up to 72 hours
Corps	up to 96 hours

Figure 2.1 shows the inter-relationship of the areas of influence and interest for a corps. The key feature is the stacking of the areas of influence and interest of a subordinate unit within the area of influence of the next higher unit. Each unit is responsible for collecting information within its area of influence. The means to do this are the organic and supporting assets. The primary information collectors at each level are detailed below:

- Battalion: Tank/Infantry companies, the scout platoon, ground surveillance radar (GSR) sections, and artillery fire support teams (FIST) are the usual collectors.

- Brigade: Divisional brigades generally do not possess organic assets for the collection of information. Rather, they task their subordinate battalions to perform the required collection of information within the brigade's area of influence.

- Division: In addition to subordinate brigades, the cavalry squadron, military intelligence battalion, divisional artillery target acquisition units, NBC reconnaissance platoon, air defence battalion and divisional engineer and aviation units are the primary collectors.

- Corps: In addition to subordinate divisions and separate brigades the normal collectors are armored cavalry regiments, artillery units, military intelligence groups, aviation groups, engineers and adjacent corps.
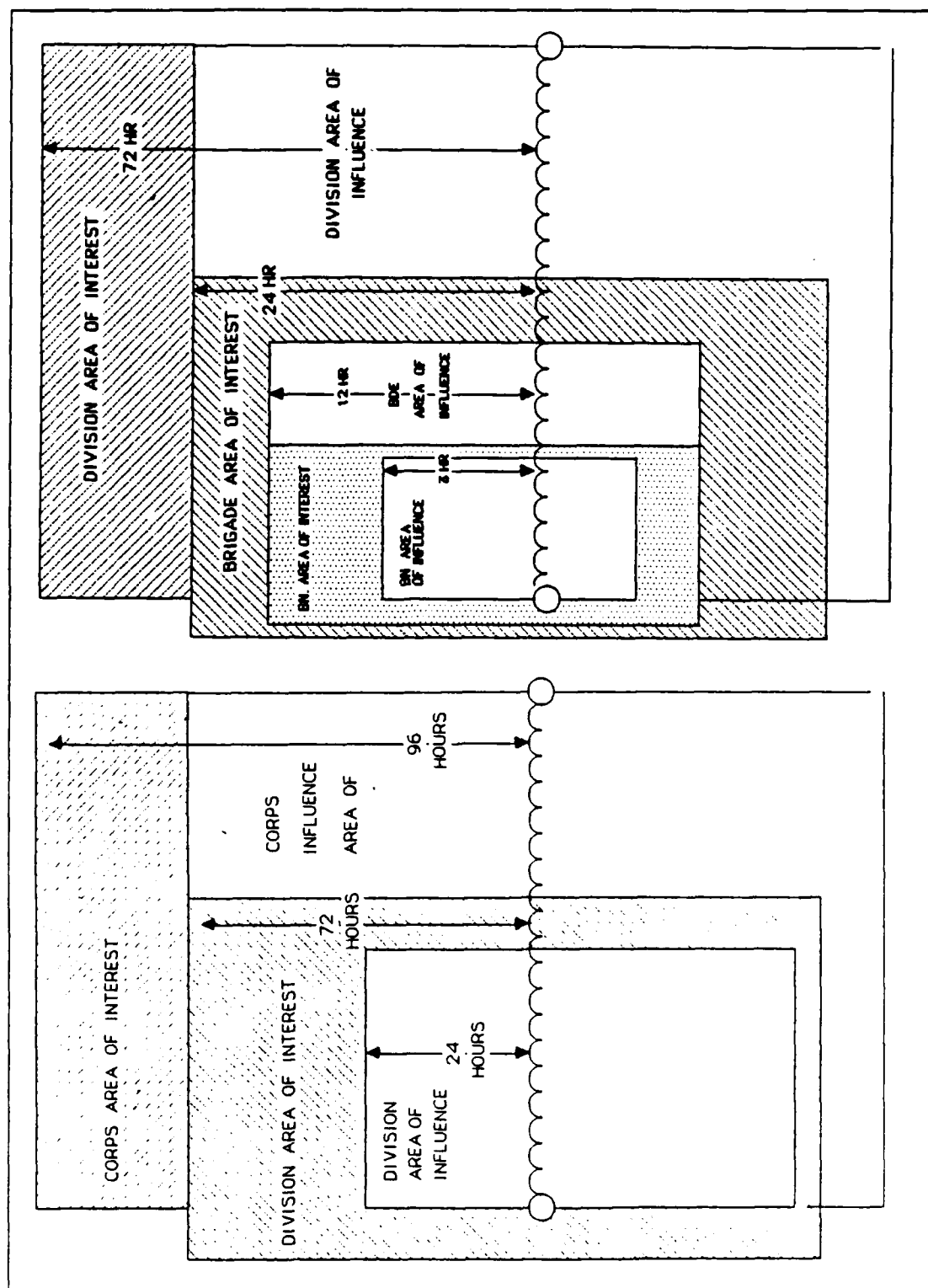
Figure 2.1   Areas of Interest and Influence.

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Figure 2.2 is a simplified diagram of the flow of information, combat information and intelligence into and out of a unit intelligence organization. Information flows into the intelligence section from collectors which are operating in the unit's area of influence. The intelligence section identifies combat information contained in the raw information and passes this to the commander, associated staff elements, subordinate units and the senior units intelligence section as appropriate. The intelligence section also receives combat information from all of these same agencies. This combat information is disseminated as required and, coupled with intelligence from the senior headquarters, is used to prepare and update the intelligence estimate. This intelligence estimate is essential to the commander and his staff in planning and conducting operations.

Two unique features of the intelligence system are illustrated in Figure 2.2. First, unlike combat information, intelligence only flows down the chain of command. Subordinate units do not pass intelligence to senior units. This may seem like an unreasonable constraint on the flow of critical information, but in reality it is merely an artifice of the distinction between combat information and intelligence. Tactical intelligence is combat information which has been processed and specifically tailored to the unit's mission. It is necessarily limited in scope and contains suppositions about the enemy. There actually tends to be a healthy, but unofficial, dialogue between intelligence organizations about enemy capabilities and potential actions. The second unique feature is that information does not flow exclusively into the intelligence section. Information flows into the commander and the other staff sections of the unit. This information receives minimal processing (verification/validation) and then enters the intelligence system as combat information.

With this as a basis for understanding the tactical intelligence system, the next step is to construct a model which replicates the functions and results of the system.

B. THE INTELLIGENCE MODULE

The architecture of the proposed Intelligence Module and its relationships with the Planning Module and Execution Module is displayed in Figure 2.3 Notice that the Planning Module is structured so that there is a sub-planning module for each hierarchical level of the organization. The Intelligence Module is sub-divided along the same lines. Associated with each sub-planning module is an intelligence sub-module. Each intelligence sub-module consists of two components; the Combat Information

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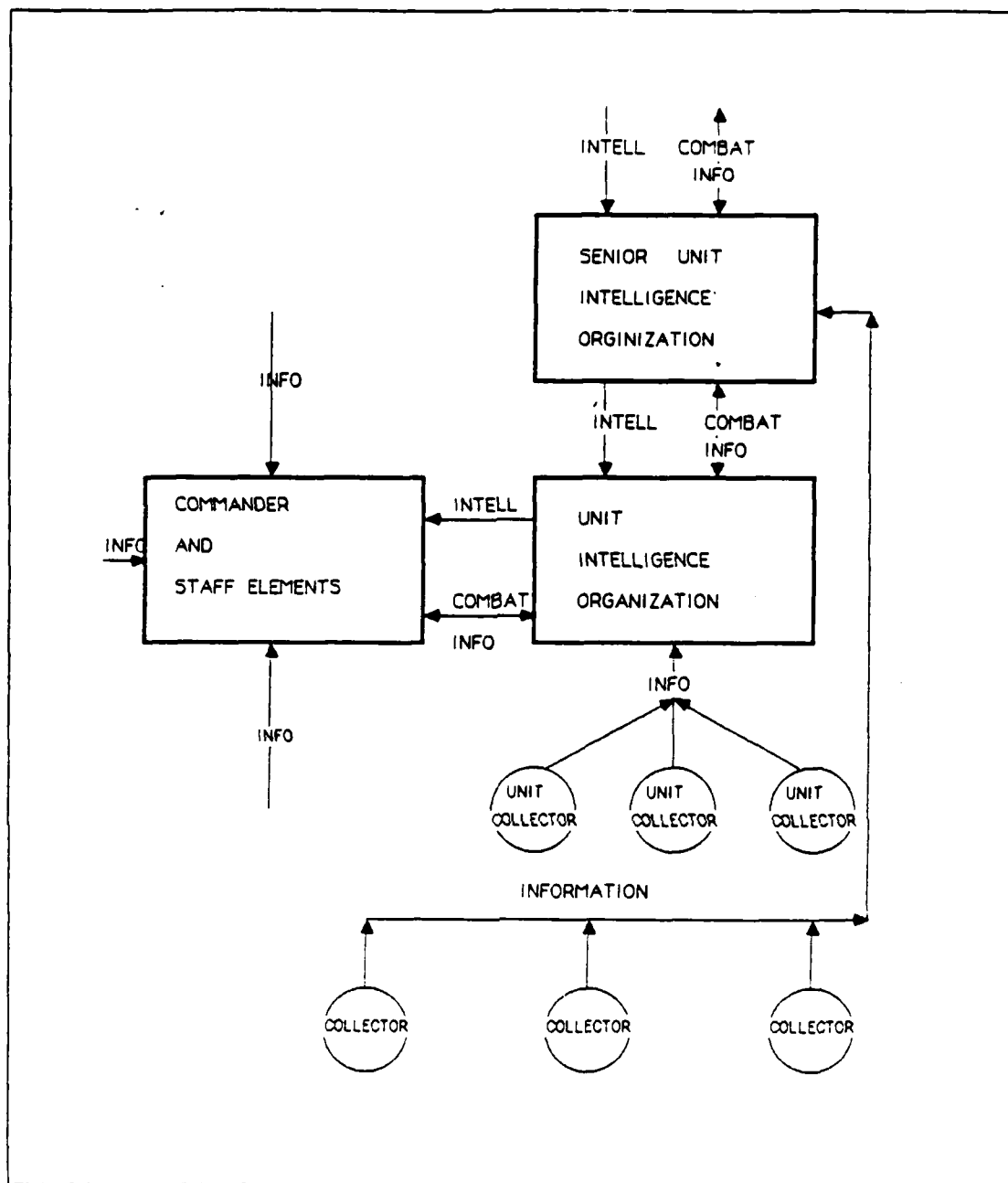
Figure 2.2   Information Flow.

Processor (CIP) and the Intelligence Estimate Processor (IEP). All information, both friendly and enemy, is routed to a CIP. Updates in friendly unit status such as location or strength, the destruction of a bridge and contact with an enemy unit are examples of information which could be received from the Execution Module.
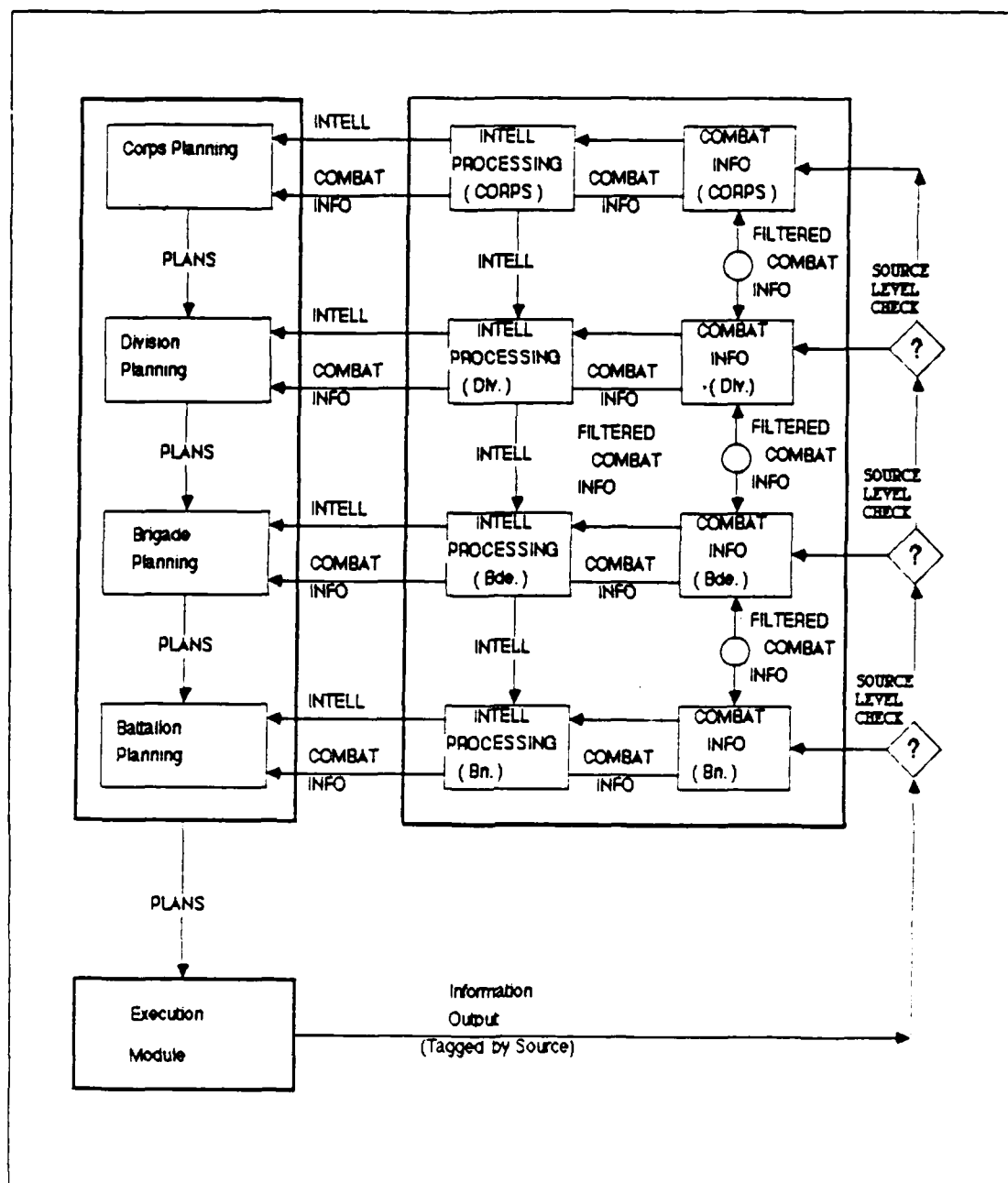
Figure 2.3   ALARM Modules.

In order to illustrate the proposed model a typical item of combat information will be traced through the system, in this case a sighting of a group of enemy tanks reported by a battalion's GSR. Information from the Execution Module is tagged by

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the collector which is reporting the information. This collector is identified on the task force hierarchical network as belonging to a particular unit. This task force tag is used to route the information to the correct battalion CIP. In the CIP the incoming information is compared to the current perceived data base. The CIP must determine if the reported group of tanks is a first time sighting of a previously unknown enemy unit, a redundant sighting which has been reported by another collector or an update on an already known enemy unit. The method by which this checking is conducted and the aggregation methodology are described in Chapter III.

Assume that in this specific instance the group of tanks is determined to be a new target. The CIP updates the battalion's perceived data base by adding the enemy tanks. This perceived data base is used both by the battalion's planning sub-module and the IEP component of the battalion's intelligence sub-module. Additionally the combat information concerning the tanks is passed to the CIPs of the battalion's subordinate units and to the CIP of the next senior unit in the task force hierarchy. As indicated in Figure 2.3 the combat information reported up and down the chain of command may be filtered. In the downward flow of combat information this filtering serves as a sieve. Aggregated information is broken down into blocks that are appropriate for the level receiving the combat information. Conversely the filtering serves to aggregate the combat information which is passed up the task force network. Thus, for example, battalions would receive data on the location of platoons whereas divisions would receive data on battalions and regiments. It is currently conjectured that the EEI, augmented by a standardized set of reporting criteria, will form the basis for the filtering.

The Intelligence Estimate Processor (IEP) is the second component of the Intelligence sub-module. As previously stated the IEP operates on the perceived data base of the organization and the intelligence estimate of the next higher unit. The purpose of the IEP is to prepare an intelligence estimate which will be used by the planning sub-module of the organization. The specific purpose of the IEP is to identify enemy units, by type and designation, and to predict their courses of action. This is a somewhat restricted version of an actual intelligence estimate which would additionally consider the effect of terrain on the friendly units ability to accomplish its mission. In ALARM, as currently conceived, the Planning Module will determine the influence of terrain on the friendly forces. The IEP will be restricted to examining the enemy forces. Naturally, this will require that the effects of terrain on enemy forces also be

determined. It is believed that much of the ongoing effort to develop a terrain network structure, and the corresponding Planning Module which capitalizes on it, will result in a model which can be used by the IEP with only minor modifications.

Continuing the example of the detected tanks, the battalion IEP would fuse this new information with the existing intelligence estimate of the battalion. The IEP will possess the capability to aggregate enemy units and identify the parent organization. Potential enemy courses of action will be evaluated and passed to the planning sub-module. The IEP must specifically estimate the arrival time of the enemy units at selected points on the battlefield. Additionally the IEP will have a methodology which will allow it to determine the most likely enemy course of action. The intelligence estimate prepared by the IEP will develop the Situational Inherent Power (SIP) Curves for the enemy forces [Ref. 3]. These SIP Curves form the basis for the future state decision making in ALARM.

Concurrent with the development of the battalion's intelligence estimate, the IEP of the controlling brigade would be revising its intelligence estimate by incorporating the new combat information which had been passed to its CIP from the battalion. This updated brigade intelligence estimate would then flow to the subordinate units of the brigade and be used to alter their own intelligence estimates as required.

C. THE INTELLIGENCE ESTIMATE

The area of identifying and predicting the enemy's course of action forms the heart of the intelligence estimation procedure. Currently ongoing research into terrain modeling and avenue of approach determination in ALARM must be completed before the intelligence estimation methodology can be developed further. However, a promising area of research may be to develop a set of decision rules to aggregate, identify and predict enemy activity using "templates". Currently the intelligence officer develops and uses three general types of templates to assist him in preparing the intelligence estimate [Ref. 1:pp. 6-7,6-8]:

1. Doctrinal Templates - models based on enemy tactical doctrine. They portray frontages, depths, echelon spacing and force composition.

2. Situational Templates - a series of projections that portray how the doctrinal templates will appear when applied to specific terrain.

3. Event Templates - models of enemy activity. They are sequential projections of events that relate to both space and time on the battlefield. They indicate the enemy's ability to adopt a particular course of action.

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The templates are specialized to the enemy and the tactical situation. They are tools used to assist the intelligence officer, but are at best approximations. Decision rules based on templates must recognize and adjust for this lack of precision.

D. SUMMARY

The Intelligence Module consists of two components: a Combat Information Processor (CIP) and a Intelligence Estimate Processor (IEP). Information from the Execution Module is identified by the collector and flows on the task force organizational hierarchy network to the appropriate CIP. The CIP updates the perceived data base and directs the combat information to other task force elements as required. The Intelligence Estimate Processor (IEP) prepares an intelligence estimate which identifies enemy units, their locations and courses of actions. The IEP also develops the SIP curves for the enemy units which is used by the Planning Module. Intelligence flows down the task force hierarchy. The Intelligence Module serves as the funnel for all information between the Execution Module and the Planning Module.

III. THE COMBAT INFORMATION PROCESSOR

The previous chapter addressed the proposed Intelligence Module and its two components, the Combat Information Processor (CIP) and the Intelligence Estimate Processor (IEP), in general. This chapter further develops the concept of the CIP, its relationships to the Execution Module and IEP. It specifies the information which must be passed from the Execution Module and IEP to the CIP and the method by which this is accomplished. Figure 3.1 shows the linkages between the Execution Module, the CIP and the IEP; the functions of each are indicated. The logic by which the CIP processes incoming reports is diagrammed in Figure 3.2 The next sections discuss the internal CIP logic and propose specific methodology.

A.   TARGET VECTORS

Target acquisition is performed in the Execution Module and the results passed to the appropriate CIP by means of a target vector. When a scanning unit acquires an entity a target vector is created. This target vector is unique and remains in existance as long as the scanning unit is able to track the entity. A target vector consists of the following components:

- I_1, I_2 - the entity's true identification code and a target number assigned by the scanning unit. The identification code, I_1, is used by the Execution Module to address the correct entity for computations. Each entity on the battlefield will have a unique identification code number. The target number, I_2, is a temporary identification code used by the CIP and IEP. The target number is not unique, but rather is created when the entity is acquired. If the entity is "lost" to the scanning unit and subsequently acquired again a new target number is created.

- $X_1,...,X_k$ - the true current size (number) of each of the elements of which the entity is composed.

- $Y_1,...,Y_k$ - the current pcrceived (acquired) size (number) of each of the target elements contained in the entity.

- $D_1,...,D_k$ - the number of target elements which have been acquired this iteration.

- A - an activity code which describes the entity's current perceived combat activity or status. For example possible combat activities are attack, defend, withdraw,

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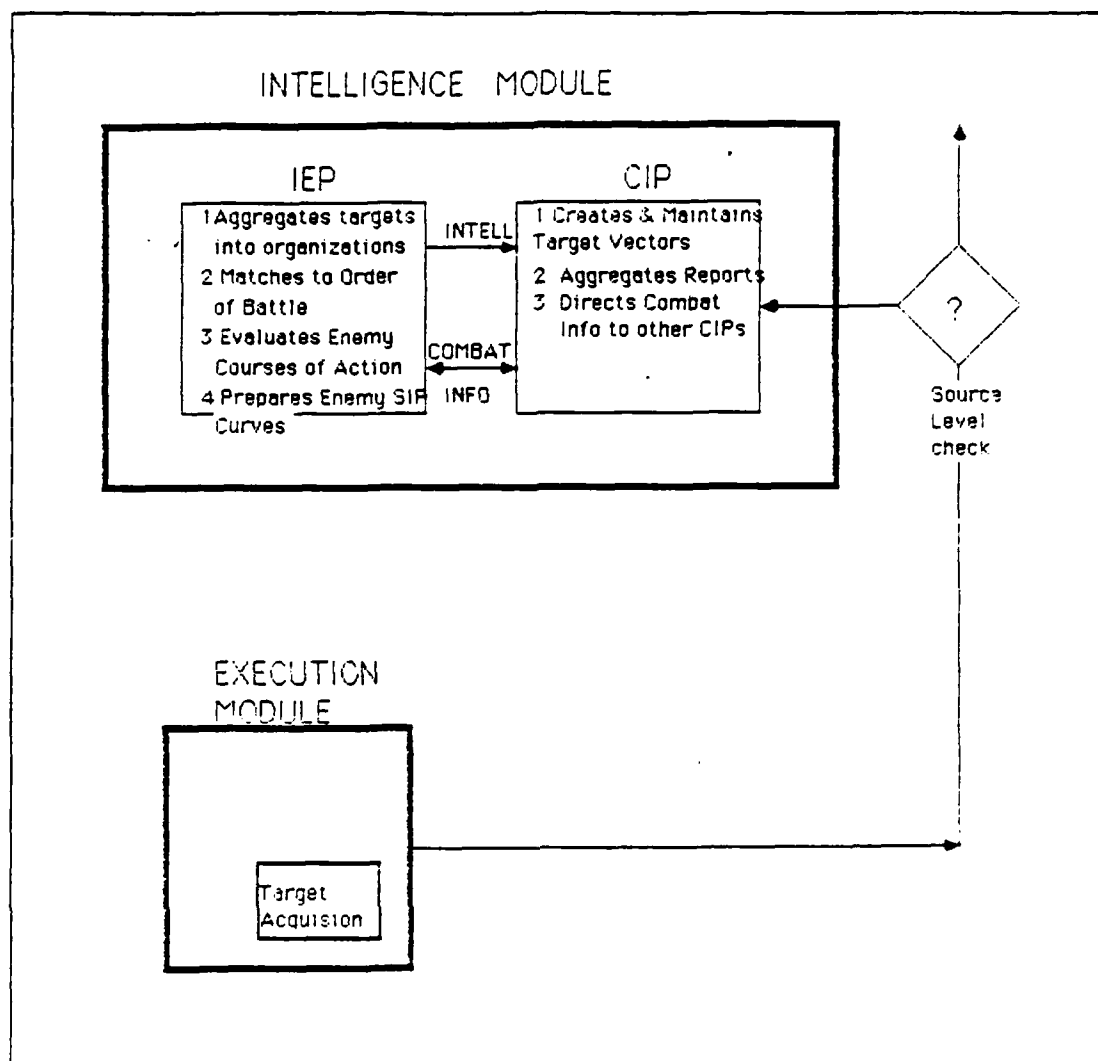
Figure 3.1   Functions of the Intelligence Module.

delay, movement to contact, tactical movement while not in contact, etc. Status codes also apply to geographic entities on the battlefield such as bridges, tunnels, railheads and airfields. These status codes describe the current perceived state of the geographic entity.

- V - a velocity vector which specifies the speed and direction of the target.
- L_1, L_2 - the true and perceived location , respectively, of the target. Results from the Execution Module are always reported based on the true location. The perceived location results from decision algorithms which aggregate and classify targets.

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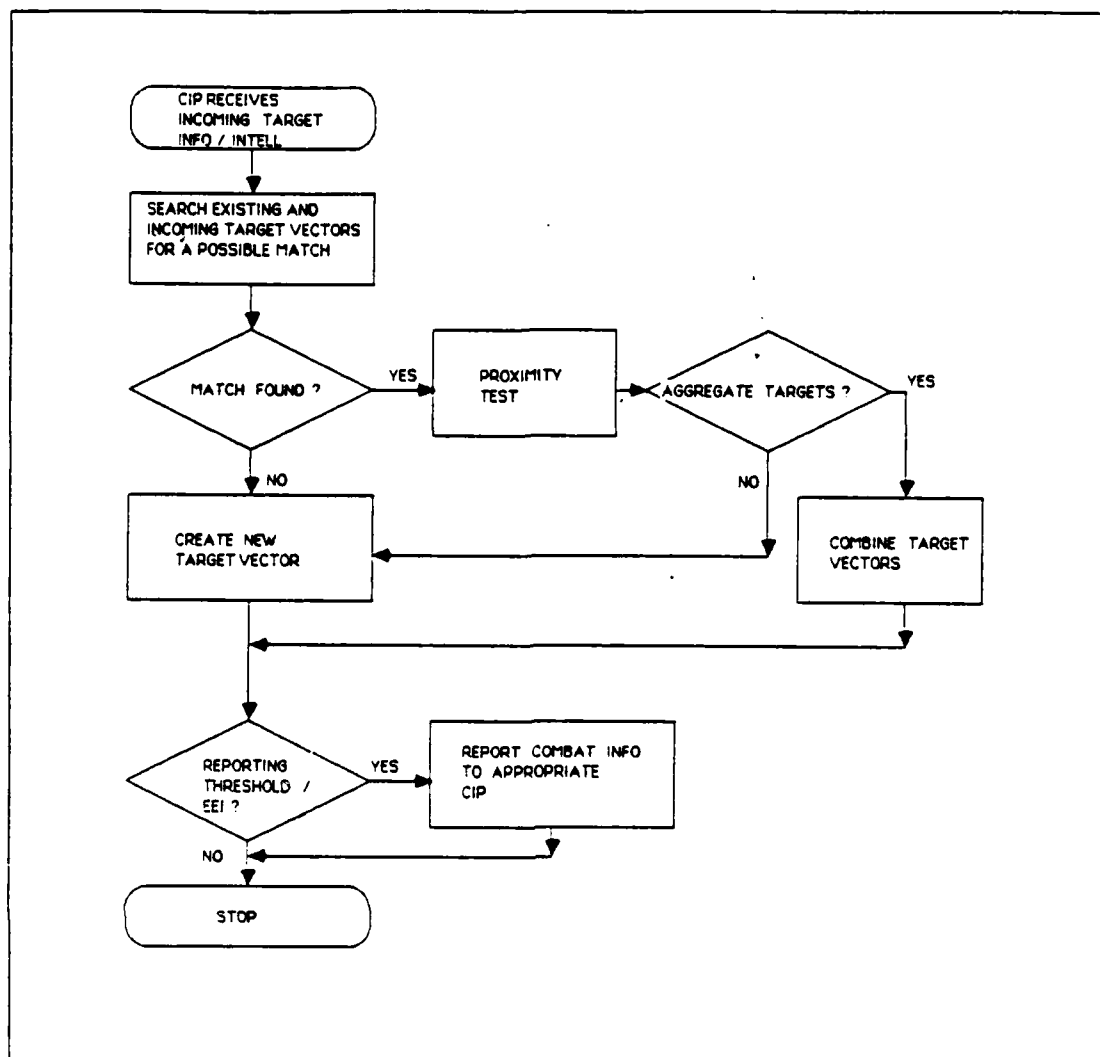
Figure 3.2   CIP Logic Flow.

- T - time of the report.
- U - identification code of the unit (sensor) reporting the information. This code is used to route the report to the correct task-force CIP.
- C - a classification code provided by the IEP. This code has several levels. At the lowest level it indicates the perceived unit size and type of the target. For example a tank platoon or motorized rifle battalion. At the intermediate level it identifies targets which are subordinate units to a larger organization. As an example three targets are identified as tank companies belonging to the same

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tank battalion. Finally, at the highest level, a target may be identified as being a specific unit listed in the order of battle, e.g., the 1st Regiment of the 55th Motorized Rifle Division. This classification is not necessarily the ground truth, but rather is the result of the decision algorithms used by the IEP.

Since an acquired target does not necessarily remain acquired the current number of acquired target elements can eventually decrease to zero. When this happens the target vector for enemy units is deleted. As acquisition is lost the classification code, C, remains at the highest level reached (unless it is changed by the IEP). Thus the gradual loss of acquisition represents the degrading of information about a specific target. Conversely, a target vector for a geographic entity is not deleted when acquisition is lost; it remains unchanged from the last observation. Essentially, the information about a geographic entity's status ages after acquisition is lost and may not be accurate.

B.   DETERMINING THE PERCEIVED TARGET SIZE

Each CIP will be receiving reports from one or more subordinate units represented in the Execution Module. The CIP can therefore receive more than one report about the same target. Each of these reports can differ in the number of target elements acquired. The CIP must be able to determine the number of target elements which have been acquired given the number reported by different subordinate units. Three simple methods for determining the perceived number of acquired target elements are proposed.

- Method A : Assume there is no overlap in the reported target elements. That is, each report represents distinct target elements which have not been reported by any other collector. Under this method the perceived number of target elements acquired is:

$$\text{Acquired} = \min (D_i, X'_i) \tag{3.1}$$

where

D_i = the total number of the ith target elements reported newly acquired this iteration

X'_i = the true number of target elements remaining unacquired.

Example 3-1

A CIP has three collectors which report the following number of newly acquired tanks, from the same target

$$d_1^1 = 6$$

$$d_1^2 = 8$$

$$d_1^3 = 10$$

where

d_1^j = the jth report about target element 1 .

The true number of unacquired tanks is 20. In this method the perceived number of newly acquired tanks is:

$$min (24,20) = 20 .$$

- Method B: Assume that there is maximum overlap in the reported target elements. Each target element is reported at least once. The largest report is the upper bound on the number of newly acquired target elements, and the remaining reports are subsets. The perceived number of target elements acquired is:

$$Acquired = max(d_i^1,...,d_i^n) \qquad (3.2)$$

Example 3-2

Using the data from Example 3-1 the perceived number of acquired tanks is:

$$max (6 ,8, 10) = 10 .$$

- Method C: Assume that the number of newly acquired target elements is bounded by the smallest and largest reports. A weighted averaging technique is then used to determine the perceived number of target elements acquired. Weighting is required to place emphasis on those reports which are more credible. A simple weighting factor could be based on the range separating the collector from the target, the battlefield environment and the sensor type. Consider the following weighting function:

where

r = range separating the collector and the target

rmax = the maximum range at which the collector is effective

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$$W = 1 - (r/rmax)^g \quad \text{for } 0 \leq r \leq rmax \qquad (3.3)$$

(depends upon battlefield conditions)

g = a shaping constant which is determined for each

.collector / target combination (can be adjusted

for battlefield conditions).

The shaping constant, g, may be a function of the attenuation coefficient found in many high resolution models of target detection.

The perceived number of the ith target element acquired by the jth collector is given by:

$$\sum_{j=1}^{J}(W_i^j \times d_i^j) / (\sum_{j=1}^{J}W_i^j) \qquad (3.4)$$

Example 3-3

As in Example 3-1, each CIP has three collectors reporting to it. Each collector has the weighting function

$$W_i = 1 - (r_i/5000)^1 .$$

The following reports are made:

$$d_1^1 = 6 \quad , r_1 = 4500$$

$$d_1^2 = 8 \quad , r_2 = 2000$$

$$d_1^3 = 10 \quad , r_3 = 500$$

The weights are calculated to be:

$$W_1^1 = 0.1$$

$$W_1^2 = 0.6$$

$$W_1^3 = 0.9$$

The perceived number of acquired tanks is:

$$[(.1 \times 6) + (.6 \times 8) + (.9 \times 10)] / [.1 + .6 + .9] = 9 .$$

Of the three methods presented, weighted averaging provides the most flexibility. The perceived number of acquired targets can be easily adjusted for range, battlefield

conditions and sensor (collector) type. It is important, regardless of the method chosen, that the results are consistent with the target acquisition methodology adopted for use in the Execution Module.

C.   AGGREGATING TARGETS

A CIP' receives target information from its collectors through the Execution Module, filtered combat information from senior and subordinate CIPs, and intelligence from the associated IEP. The CIP must possess an algorithm which determines if a new target vector should be created or existing target vectors combined into a single target vector. A modification of a methodology proposed by Lindstrom can be used to aggregate target vectors when required [Ref. 4]. A basic assumption is that the error in the reported target location follows a circular normal distribution. A target generally consists of several target elements but is reported as a single location. The error in question measures the collector's ability to accurately judge the true target center, not its ability to locate specific target elements. The test is composed of two steps; a similarity check and a proximity test. If the decision is made to combine the targets, an adjusted location is calculated. The algorithm is:

TABLE 3
MATCHING OF TARGETS

Incoming Target Y	Existing Target X_1 (Score)	Existing Target X_2 (Score)	Existing Target X_3 (Score)
Tank	Tank (1)	Tank (1)	
BMP	BMP (1)	BMP (1)	
Arty	Arty (1)		
			ZSU-23 (0)
			SA-8 (0)
Rank	3	2	0

Step 1. Check the incoming target vector against current target vectors for matches in perceived target element types. The matching algorithm proposed by Lindstrom searches the existing target vectors for a single match in target element type between the newly reported target and the existing targets. This algorithm can be modified slightly to consider a heterogeneous forces composed of several different target element types. The purpose of the algorithm is to match the incoming target with a similar type target. The size of the targets is not considered when attempting to find a match, this issue is addressed by the aggregation algorithm.

The proposed methodology ranks potential matches between the existing target vectors and the incoming reported target. Each target element type of the reported target is compared to each target element type of an existing target vector. For each target element type match between the two targets a "1" is scored. For each target element type which is not matched a "0" is scored. The rank of the potential match is merely the sum of the scores. Ties in the ranks can be resolved by considering such factors as: terrain, enemy situation and projected enemy courses of action. As the terrain model and the intelligence estimation procedures are developed the matching algorithm can be refined to consider more information about the target and potential matches (e.g. avenues of approach and activity status). Starting with the highest ranking potential match the proximity test is conducted until an aggregation takes place, or all matches have been considered. If no matches are found (i.e., all ranks are 0) a new target vector is created. As an example consider the targets vectors shown in Table 3. The incoming target, Y, is compared to the three existing target vectors, X_1, X_2 and X_3. Three target element matches are found between Y and X_1, two matches between Y and X_2 and no matches between Y and X_3. Since X_1 has the highest rank it would be considered first when attempting to aggregate targets. If Y and X_1 were not combined into a single target the aggregation procedure would next consider X_2. Finally, if Y and X_2 were not combined a new target vector would be created for Y.

Step 2. Conduct the proximity test - The null hypothesis to be tested is that the reported target location means are the same:

$$H_0 : (\mu_{X_1}, \mu_{Y_1}) = (\mu_{X_2}, \mu_{Y_2})$$
$$H_1 : (\mu_{X_1}, \mu_{Y_1}) \neq (\mu_{X_2}, \mu_{Y_2})$$

a. Using a table look up, determine the circular error probable (CEP) associated with each target report and compute the standard deviation for each. The circular normal

assumption leads to the following relationship between the CEP and standard deviation:

$$\sigma_i = CEP_i/1.774 \tag{3.5}$$

b. Calculate the square of the distance between the reported locations.

$$D^2 = (X_1 - X_2)^2 + (Y_1 - Y_2)^2 \tag{3.6}$$

c. Compute the test statistic

$$T = D^2 / (\sigma_1^2 + \sigma_2^2) \tag{3.7}$$

(note T is distributed χ_2^2 = exponential (λ = 1/2).

d. If $T \leq \chi_2^2(\alpha)$ then accept H_o and combine target vectors.

e. If targets are combined calculate location as:

$$X' = \{X_1 \times (r_1 + s_2)/2\} + \{X_2 \times (r_2 + s_1)/2\} \tag{3.8}$$

$$Y' = \{Y_1 \times (r_1 + s_2)/2\} + \{Y_2 \times (r_2 + s_1)/2\} \tag{3.9}$$

where

r_1 = (size of target 1) / (size of target 1 + size of target 2)
r_2 = (size of target 2) / (size of target 1 + size of target 2)
$s_1 = \sigma_1/(\sigma_1 + \sigma_2)$
$s_2 = \sigma_2/(\sigma_1 + \sigma_2)$

The size of a target is measured as the number of primary fighting elements that it has. The ratio of the sizes, r_1 and r_2, act as a weighting factors. Without these weighting factors it would be possible for a small target, which has a relatively small CEP associated with it, to dominate when calculating the adjusted position. Similarly, s_1 and s_2 act as weighting factors which compensate for the CEP of each target.

Example 3-4

A battalion CIP receives an intelligence update from its associated IEP. The IEP, based on an intelligence estimation procedure, indicates that there is a motorized rifle company, consisting of BMPs and tanks, located in the vicinity of cartesian coordinates (550,765). The CEP for this type and size of unit is assumed to be 200 meters, for the purpose of the example.

- Step 1. Checking the existing target vectors the battalion CIP identifies a potential target consisting of 4 BMPs and 2 tanks located at (400,700) with a CEP of 150 meters. The selected target vector has a rank of two since it matches both target element types of the incoming target vector.

- Step 2.

    a. Compute the associated standard deviations.

$$\sigma_1 = 200 / 1.774 = 112.74$$
$$\sigma_2 = 150 / 1.774 = 84.55$$

    b. Calculate the square of the distance between the reported locations.

$$D^2 = (550\text{-}400)^2 + (765\text{-}700)^2 = 26725 .$$

    c. Compute the test statistic.

$$T = 26725/(12710.31 + 17148.70) = 1.35$$

    d. Using the relationship between the χ_2^2 and the

    exponential (1/2) distributions, the $.95^{th}$ quantile is given by:

$$Q.95 = -2 \ln (1\text{-}\alpha) = 5.991 \tag{3.10}$$

    since $T = 1.35 \le Q.95 = 5.99$

    do not reject the null hypothesis and combine the targets.

    e. The combined target location is calculated by

$$r_1 = 10/(10 + 6) = 0.63$$
$$r_2 = 6/(10 + 6) = 0.38$$
$$s_1 = 112.74/(112.74 + 84.55) = 0.57$$
$$s_2 = 84.55/(112.74 + 84.55) = 0.43$$

    so

$$X' = [550(0.63 + 0.43)/2 + 400(0.38 + 0.57)/2]$$
$$= 481.5 \sim 482$$
$$Y' = [765(0.63 + 0.43)/2 + 700(0.38 + 0.57)/2]$$

$$= 737.95 \sim 738$$

The CIP now has a single target vector classified as a motorized rifle company, centered at (482 , 738), of which 4 BMPs and 2 tanks have been acquired.

By combining the target vectors two errors could have resulted. First, the targets were wrongly combined and there are actually two separate targets. Second, the targets were correctly combined but the adjusted location is incorrect. Subsequent reports from the Execution Module, which uses the true location, may allow both of these types of errors to be corrected. If there are two different targets, and the distance which separates them eventually increases, the null hypothesis may be rejected and the targets disaggregated at some point in the future. The location error is corrected in an iterative manner as the projected perceived location (based on the velocity components of the target vector) is compared to the true location reported in subsequent updates from the Execution Module. Kalman filtering may provide a method for recursively updating the estimate of the position.

D.   COMMUNICATION OF COMBAT INFORMATION BETWEEN CIPS

Each CIP receives direct reports (from the Execution Module) only from those collectors which are immediately subordinate to it. Thus a battalion CIP obtains (raw) information only from those sensors assigned to the battalion. Combat information, however, is passed between CIPs based on task force organization. Not all combat information is shared; rather it is filtered using a set of decision rules, and then passed to the appropriate CIP as required. Combat information can either be passed to a higher CIP or to subordinate CIPs. Lateral communication between CIPs is not done directly, rather combat information is passed up to the first CIP which is senior to both and then flows down. For example, in order to pass combat information between two brigades, which are controlled by different divisions, combat information would have to travel to the corps CIP and then back down to each brigade. From this example it can be seen that the filtering which takes place must occur in both directions (subordinate to senior, senior to subordinate). A set of simple decision rules, which mimic those used in actual practice, is proposed.

1. Subordinate to Senior Reporting

A general rule applied in practice is that units "look down two levels" when planning to fight. The planning unit requires combat information on enemy activity at

least one level down from this. Therefore, combat information about enemy units, would be reported to the next senior level when it meets the following threshold shown in Table 4 .

TABLE 4
REPORTING THRESHOLDS

UNIT	THRESHOLD
Battalion	Squad/Veh.
Brigade	Platoon
Division	Company
Corps	Battalion

Initial reports of enemy contact would be reported to the next senior level when contact is first established; thereafter updates would only occur if a target was at or above the threshold. For example, a battalion CIP receives a report from a subordinate unit about a new target sighting of a single tank. This combat information would flow up the CIP hierarchy and eventually reach the corps CIP. This merely serves as an alert of enemy activity and allows senior CIPs and IEPs to come on line to begin the intelligence estimate. Follow-on reports would be filtered in accordance with the established hierarchy. Thus, the brigade CIP would not receive further information on the target until it had been classified as a platoon by an IEP, or contact lost.

2. **Senior to Subordinate Reporting**

A senior CIP may receive raw information from collectors which are operating directly for it and bypass lower echelons in the task force organization. An example is division reconnaissance elements which operate forward of the brigades area of influence. Additionally the senior CIP will receive combat information from the next higher level CIP. This combat information must be disseminated to the subordinate units. Under this proposed methodology subordinate units would receive combat information from the next senior unit whenever a target entered the subordinates area of interest. Combat information on enemy units would be disaggregated, based on the established thresholds, and directed to the CIP in whose area of interest the target was located. Since areas of interest overlap, the target may be reported to more than one subordinate CIP.

A special case involves items of combat information which have been declared Essential Elements of Information (EEI). EEI are not subject to the normal threshold restrictions imposed on other combat information. Combat information concerning EEI is always passed up, or down, the CIP hierarchy to the appropriate CIP.

E.   SUMMARY

The CIP is responsible for creating and maintaining the perceived data base for each organizational level within ALARM. It does this by creating, combining or deleting target vectors based on reports from the Execution Module, the associated IEP, and other CIPs. Information received from the Execution Module is always based on ground truth (i.e., there is no built-in error). Deviations from ground truth arise because of the decision algorithms used by the IEP and CIP sub-modules.

Further development of the Intelligence Estimate Processor is contingent upon the completion of ongoing research on the network representation of ALARM entities and generation of avenues of approach.

IV. TARGET ACQUISITION

A. MODELING TARGET ACQUISITION

Potential targets occupy a very small fraction of the total available space in the combat area. This makes it almost impossible to destroy undetected targets. Any combat model must deal with the method by which targets are acquired by the opposing forces. The first step is to determine what is meant by target acquisition.

Hartman [Ref. 5:pp. 4-1,4-2] has identified several levels of target acquisition. He has summarized these levels as follows:

- Localization - the determination from cueing information of the approximate location; used to focus further search.

- Detection - the decision by an observer that an object in his field of view is of military interest.

- Classification - the determination by an observer that the object is member of a broad target category.

- Recognition - the discrimination among finer target classes of a target's class.

- Identification - the establishment by an observer of a target's precise identity.

In the literature the terms "target acquisition" and "target detection" tend to be used interchangeably. In the remainder of this paper, to avoid confusion, the term acquisition will refer to the entire target acquisition process whereas detection will refer to a sub-level of the acquisition process. As Hartman points out:

> The response to a target acquisition depends on the level of acquisition attained. Detection may cause the observer to look more closely or use a different sensor in an attempt to gain more information. Identification may be required before combatants are allowed to engage the target. [Ref. 5:p. 4.2]

The physical attributes of a target that are the basis for its detection are often referred to as target signatures [Ref. 6:pp. 11-8,11-9]. Common signatures are:

- Trajectory - created by the path of a projectile in flight. It is detectable by radar sensors and associated with artillery and mortar weapons.

- Silhouette - the visible configuration of a target. The probability of detection is degraded by poor visibility and masking by terrain, vegetation and camouflage.

- Heat - infrared energy emitted by a target. This signature is associated with weapon firings, vehicle engines and even body heat. Heat is detected by IR sensors and affected by atmospheric conditions.
- Flash - equivalent to heat, but transmitted over the visible portion of the electromagnetic spectrum.
- Smoke/Dust - caused by weapon firings and vehicle/troop movement. This signature is observable during daylight.
- Sound - emitted by almost all targets and detectable by sound ranging sensors.
- Motion - associated with any moving object. It is detectable both visually and by radar sensors. This signature is degraded by poor visibility (in the case of visual observation), terrain and vegetation masking and distance. Accuracy of location is further degraded by the motion itself.

In addition to the factors listed above which degrade a specific target signature, there is the common factor of range.

Any target detection model must consider, either explicitly or implicitly, both the signatures and the factors which degrade them. Additionally, it is useful to develop a model that is based on target categories. The Engineering Design Handbook (DARCOM-P 708-101) [Ref. 6:pp. 11-2,11-4] defines the following target categories:

- Point Target: A target which usually consists of a single target element. It is assumed to have dimensions that are small in comparison to the range between the weapon (sensor) and the target.
- Area Target: A two dimensional target which can consist of one or more target elements (e.g., a long bridge or an infantry company, in which the target elements are the individual infantrymen).
- Simple Target: A target whose elements are functionally independent. To kill a simple target each element must be destroyed (e.g. a tank platoon).
- Complex Target: A target whose elements are not functionally independent. The destruction of one of the components will kill the entire target even if the other components are undamaged. An example of a complex target is an air defense missile site. If the fire control center is destroyed the missile cannot be launched, even if it is undamaged.
- Homogeneous Target: A target composed of target elements which are of the same type. A convoy of trucks could be a homogeneous target as opposed to a combined arms force consisting of tanks and infantry.

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- Heterogeneous Target: A target in which the individual target elements are not all of the same type (e.g., a combined arms force of tanks and infantry).
- Stationary Target: A target that is fixed or not subject to movement while under attack.
- Moving Target: A target which possesses a non-zero velocity vector.

B. ACQUISITION MODELS

To describe the stochastic nature of target detection, Koopman [Ref. 7] introduced two detection models: the glimpse model and the continuous search model. These models, in one form or another, serve as the basis for modeling the target acquisition process, for a single observer vs. a single target, in most combat simulations.

1. The Glimpse Model

In the glimpse model the observer (sensor) is assumed to have a series of distinct opportunities to detect a target. These opportunities are known as glimpses. On each glimpse the probability of detection, given that it has not occured earlier, is p_i, where the subscript i indexes the ith glimpse. The probability of detection on the nth glimpse is given by:

$$P[N=n] = p_n \times \prod_{i=1}^{n-1} q_i \qquad (4.1)$$

where q_i is $1-p_i$.

The probability of detection on or before the nth glimpse is:

$$P[N \leq n] = 1 - \prod_{i=1}^{n} q_i \qquad (4.2)$$

The probability that a target is not detected in n glimpses is:

$$P[N > n] = \prod_{i=1}^{n} q_i \qquad (4.3)$$

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A very important special case arises when the probability of detection on a glimpse remains the same for each glimpse (p = 1-q). In this case, a glimpse can be considered to be an independent Bernoulli trial and the probability of detection on the nth glimpse becomes:

$$P[N = n] = p \times q^{n-1} \qquad (4.4)$$

This is the geometric probability distribution with parameter p and n = 1,2,3,... . It follows that:

$$P[N \leq n] = 1\text{-}q^n \qquad (4.5)$$

and

$$P[N > n] = q^n \qquad (4.6)$$

Based on the geometric distribution the expected number of glimpses until detection is:

$$E(n) = 1/p \qquad (4.7)$$

And the variance is:

$$V(n) = q/p^2 \qquad (4.8)$$

Hartman [Ref. 5:pp. 4-5,4-7] notes that the numerical value of p, for the geometric distribution can be estimated experimentally. He suggests that a number of detection trials be conducted and the sample mean (XBAR) computed. Since the sample mean is the maximum likelihood estimater of E(n):

$$E(n) = 1/p \sim XBAR \qquad (4.9)$$

or

$$p = 1/XBAR \qquad (4.10)$$

In order to obtain p for different conditions a series of experiments for each observational condition could be conducted and the results tabled.

2. The Continuous Search Model

The continuous search model is based on a detection rate function, $D(t)$, and the assumption that the probability of detection in a short time interval, conditioned on the failure to detect earlier, is proportional to the length of the interval. In this model the observer (sensor) maintains continuous observation. The continuous search model is developed as follows:

Let

$p(t)$ = probability of detection at or before time t.

$q(t)$ = probability of no detection at or before time t. and

$D(t)$ = detection rate function, which may depend on time.

Then

$q(t) = 1 - p(t)$

Further, $q(t + \Delta t)$, the failure to detect during time, $t + \Delta t$, is the product of the failure to detect at or before t and the failure to detect during the additional time, Δt, conditioned on the failure to detect earlier.

Thus

$$q(t + \Delta t) = q(t)[1 - D(t)\Delta t] \qquad (4.11)$$
$$= q(t) - q(t)D(t)\Delta t$$

rearranging terms

$$[q(t + \Delta t) - q(t)]/ \Delta t = -q(t)D(t) \qquad (4.12)$$

now taking the limit as $\Delta t \rightarrow 0$

$$dq(t)/dt = -q(t)D(t) \qquad (4.13)$$

This is a first order differential equation with a solution form of:

$$q(t) = C \times \exp[-\int_0^t D(s)ds] \qquad (4.14)$$

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where the time scale is chosen so that the search begins at time = 0. By further assuming that q(0) = 1, the exact solution is:

$$q(t) = \exp[-\int_0^t D(s)ds] \qquad (4.15)$$

Finally,

$$p(t) = 1 - \exp[-\int_0^t D(s)ds] \qquad (4.16)$$

which is the probability of detecting a target in a search beginning at time, 0, and ending at time, t.

A special case arises when the detection rate function D(t) is considered to be a constant, D. The probability of detecting a target becomes:

$$p(t) = 1 - \exp[-Dt] \qquad (4.17)$$

This is the cumulative distribution function (CDF) of the exponential distribution with parameter, D. It follows therefore that, in this case, the time of detection for a search during the interval, [0,t], is an exponentially distributed random variable with:

$$E[T] = 1/D \qquad (4.18)$$

and

$$V[T] = 1/D^2 \qquad (4.19)$$

Hartman [Ref. 5:p. 4-13] points out that the exponential distribution is a high variance distribution. Short detection times are most likely, but long detection times can occur. Further the exponential distribution is the continuous analogue of the discrete geometric distribution. Both the geometric and exponential models involve the assumption of independence of successive time increments and have the memoryless property. This property can be expressed as follows:

The fact that you have been searching for five minutes without success does not influence the probability of achieving detection in the next ten seconds. It is the same as if you had just begun to search now. [Ref. 5:p. 4-13]

3. The Glimpse and Continuous Search Models in a Simulation

Generally a combat simulation will fall into one of two broad categories based the manner in which the simulation time clock is handled. In the first method the simulation is advanced in a fixed time step. At each time step the simulation calls all of the subroutines, as required, and computes the results. The second method is event scheduling. In the event scheduling approach the time step is not fixed, rather the time of the next "event" is calculated and the simulation clock is advanced to that point. The glimpse and continuous search models have been adapted to both methodologies.

Both of these target acquisition models have been extensively used in high resolution combat simulations. One of the difficulties which may arise in using either model is the need to consider each sensor target combination. In a large scale model like ALARM this may prove to be prohibitive in terms of computer time. Additionally individual items are often not represented, but aggregated into macro-targets. Of course it is possible to reduce the number of sensor target combinations which must be evaluated by including a number of simple tests to screen out ineligible targets. For example, tests which might be included are friend vs enemy, range, sector, line of sight, and target class. These tests make it computationally more reasonable for a large scale combat simulation to handle point targets (both simple and complex).

Finally there is the problem of cueing. If a single target element of a target elements is detected this tends to focus further search on the same area/region. Because of this the probability of detecting the remaining targets elements may also be increased.

Many large scale combat simulations make indirect use of the glimpse and continuous-search models by using output from high resolution combat simulations to estimate the process coefficients in the large scale simulation. Hartman. Ref. states that this estimation procedure is a particularly important part of any aggregated modelling project. He further points out that many agencies maintain libraries of aggregated process coefficients to various combat scenarios so that appropriate values can be selected without having to repeat the high resolution simulation each time.

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The next section reviews Lanchester-type models of attrition and discusses their possible application to modeling acquisition in large scale combat simulations. Chapter V then presents a methodology by which the acquisition coefficients of a Lanchesterian model can be estimated from the output of a high resolution combat simulation which uses either the glimpse or continuous-search model.

C.   LANCHESTER'S EQUATIONS AND ALARM

Lanchester-type models are often used in large scale combat simulations to model attrition. In fact, ALARM will likely use Lanchester differential equations. If one is willing to accept Lanchesterian attrition, it is also appealing to believe that other frequently occurring events such as acquisition, repaired vehicles returning to the battlefield, and ammunition consumption also can be modelled by Lanchester-type equations. The key feature of all these events is that they occur often enough during the course of a battle that estimates for the time between occurances can be reasonably determined. Infrequent events, however, would not be amenable to this methodology (e.g. tactical nuclear strikes).

The preceding sections of this chapter presented two methods for modeling the target acquisition process. Point targets are handled easily by either the glimpse or continuous search models. However, the sheer number of individual sensors and targets in ALARM precludes the use of these models in many cases. This section investigates the use of Lanchester-type differential equations to model target acquisition. The use of Lanchester based models allow both force size and mix to be considered using a single methodology. Thus all classifications of targets (point/area, homogeneous/heterogeneous, and simple/complex) and sensor force sizes and mixes are covered. In the remainder of this chapter the basic homogeneous formulations for Lanchester's Laws of Combat are reviewed. Modifications of these basic laws, to include a heterogeneous formulation, are then investigated for their applicability to modeling target acquisition under a variety of conditions.

D.   LANCHESTER'S LAWS OF COMBAT

1.   First Linear Law (Direct Aimed Fire)

In this case the attrition rate is constant. There is no concentration of forces allowed, thus the battle consists of a series of individual engagements. Lanchester's First Linear Law is:

$$dX/dt = -a \text{ with } X(0) = X_0 \tag{4.20}$$

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and

$$dY/dt = -b \quad \text{with } Y(0) = Y_0 \qquad (4.21)$$

where

      $X = X(t) = $ the size of the X force at any time t.

      $Y = Y(t) = $ the size of the Y force at any time t.

      $a = $ the constant rate at which the X forces are lost per unit time (attrition coefficient).

      $b = $ the constant rate at which the Y forces are lost per unit time (attrition coefficient).

      $X_0 = $ initial X force size.

      $Y_0 = $ initial Y force size.

and

      $t, a, b \geq 0.$

In this case the solution of the differential equations are:

$$X = X_0 - at \quad \text{for } X \geq 0 \qquad (4.22)$$
$$Y = Y_0 - bt \quad \text{for } Y \geq 0 \qquad (4.23)$$

The length of time required to annihilate the X force is:

$$t_{ann} = X_0/a \qquad (4.24)$$

and for the Y force the time to annihilation is:

$$t_{ann} = Y_0/b \qquad (4.25)$$

(note: Only one of these may occur, either the X force is annihilated or the Y force is annihilated, but not both.)

      This Linear Law can easily be applied to acquisition by letting:

      $X = X(t) = $ the number of unacquired elements of the X force at any time t.

      $a = $ the detection rate $ = 1/$(mean time to detect).

$X_0 =$ the initial unacquired X force size.

Now, the number of X forces which remain unacquired at any given time t is:

$$X = X_0 - at$$

and the time required to totally acquire the X force is simply:

$$t_{acq} = X_0/b .$$

This formulation may be useful for modeling target acquisition when a sensor's scanning field is severely restricted due to terrain, vegetation and/or battlefield obscurants. Under these circumstances the scanning force will not be able to concentrate sensors by assigning overlapping sweep sectors. Also, if a sensor's sweep sector is narrow enough, only a single potential target may be able to occupy the sector at a given time. In dense vegetation (e.g., jungle) the defenders seldom have overlapping fields of view. These fields of view also tend to be only a few meters deep or wide. Correspondingly, the attacking force's ability to maneuver is also limited, and the attackers will tend to move in column formations. Therefore, as the attacking force moves through the defended area, acquisition as well as attrition may occur at a constant rate.

2. Second Linear Law (Area Firing)

Here the assumptions are that the firing is unaimed and is concentrated in an area occupied by a combatant. Additionally, the size of the area is independent of the combatant's size. Thus the attrition for the X force is proportional to the number of Y forces firing into the area and the density of the X forces in the area. The differential equations are:

$$dX/dt = -aXY \quad \text{with } X(0) = X_0 \tag{4.26}$$

and

$$dY/dt = -bYX \quad \text{with } Y(0) = Y_0 \tag{4.27}$$

A solution of the equations is:

$$X = \{-X_0(k-1)\exp[-bX_0(k-1)t]\} / \{\exp[-bX_0(k-1)t]-k\} \tag{4.28}$$

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and

$$Y = \{-Y_0(k\text{-}1)\}/\{\exp[-bX_0(k\text{-}1)t]\text{-}k\} \tag{4.29}$$

where

$$k = aY_0/bX_0 \tag{4.30}$$

The X to Y ratio at any time t is:

$$X/Y = (X_0/Y_0)\exp[-bX_0(k\text{-}1)t] \tag{4.31}$$

so that in a fight to the finish the X force wins when
$$k < 1.0$$
and Y wins when
$$k > 1.0 .$$

An alternate form of the solution is:

$$X = \{-X_0(k'\text{-}1)\}/\{\exp[-aY_0(k'\text{-}1)t]\text{-}k'\} \tag{4.32}$$

and

$$Y = \{-Y_0(k'\text{-}1)\exp[-aY_0(k'\text{-}1)t]\}/\{\exp[-aY_0(k'\text{-}1)t]\text{-}k'\} \tag{4.33}$$

where

$$k' = bX_0/aY_0 \tag{4.34}$$

In a fight to the finish the X force wins when
$$k' > 1.0$$
and Y wins when
$$k' < 1.0.$$

In both cases if $k = k' = 1$ then, although the number of X and Y forces vary during the battle, their ratios remain constant and the battle is a draw.

Lanchester's Second Linear Law seems to be a reasonable model for medium to long range target acquisition. The scanning force in this case is unable to concentrate its sensors on a specific target because of the need to cover a relatively large area. This formulation has an interesting application to target acquisition where targets have the ability to suppress searching sensors (it is assumed here that once a sensor is suppressed it remains so). If, as before,

   X = the number of unacquired elements of the X force at time, t

   a = the detection rate

X_o = the initial unacquired X force size

and

   Y = the number of unsuppressed sensors of the Y force at time, t

   b = the rate at which sensors can be suppressed

Y_o = the initial unsuppressed Y force sensors

the solutions now give the number of unacquired targets and unsuppressed sensors, respectively, at any time, t.

3. Square Law

In this case the attrition rate is directly proportional to the numerical strength of the opposing force involved in the battle at that time. This allows forces to be concentrated. As opposed to the First Linear Law assumption, where the battle was a series of individual fights, now a group of combatants can concentrate their capabilities on a single opponent. Under the right circumstances this will allow a numerically inferior force to defeat a larger one. The differential equations are:

$$dX/dt = -aY \quad \text{with } X(0) = X_o \tag{4.35}$$

and

$$dY/dt = -bX \quad \text{with } Y(0) = Y_o \tag{4.36}$$

The force levels at any time t are given by:

$$X = .5\{(X_o - \sqrt{a\,b}\ Y_o)\exp(\sqrt{ab}\ t) + (X_o + \sqrt{a\,b}\ Y_o)\exp(-\sqrt{ab}\ t)\} \tag{4.37}$$

and

$$Y = .5\{(Y_0 - \sqrt{b/a}\ X_0)\exp(\sqrt{ab}\ t) + (Y_0 + \sqrt{b/a}\ X_0)\exp(-\sqrt{ab}\ t)\} \qquad (4.39)$$

In a fight to the finish if:

$X_0/Y_0 > \sqrt{a/b}$ then the X force wins.

If:

$X_0/Y_0 < \sqrt{a/b}$ then the Y force wins.

And if:

$X_0/Y_0 = \sqrt{a/b}$ then the battle will be a draw.

      Just as a force is able to concentrate its combat power, it is also able to focus its sensors. The Square Law, depending on the sensor type, would seem to especially apply to target acquisition at short to medium ranges or when a scanning unit has prior intelligence about enemy locations . The reduced area which must be covered by the sensors will allow the scanning force to assign overlapping sweep sectors. These sweep sectors can be centered on avenues of approach into and adjacent to the position or on likely (suspected) enemy positions. Thus, acquisition will depend directly on the number of sensors available at any given time.

      These three basic Lanchester Laws can only begin to model the complex task of target acquisition. Many factors, in addition to the number of sensors and targets, influence the process. Some of the more obvious are range (separation distance), the environment, employment doctrine, and tactical scenario. Many extensions to Lanchester's basic equations have been proposed in order to make them more comprehensive. Several of these are examined next.

E. MODEL EXTENSIONS

1. Extensions for Replacement Rate

      Lanchester differential equations can be extended to account for replacement of attrited target elements. For example the Second Linear Law, with replacement, may become:

$$dX/dt = -aXY + K \qquad (4.41)$$

and

$$dY/dt = -bYX + L \qquad (4.43)$$

where

    K = the replacement rate for the X forces

    L = the replacement rate for the Y forces .

One of the fundamental differences between applying Lanchesters equations to the attrition process and target acquisition is regeneration. Once a target element is attrited it does not , under normal circumstances, rejoin the battle. This is not the case with the acquisition of targets. After a target is acquired, continuous surveillance may not be possible. If contact is lost for a long enough period, the target element essentially reverts back to unacquired status. The use of a replacement rate function, interpreted as target elements returning to an unacquired status, could be used to model this phenomenon. The rate at which target elements return to the unacquired condition would generally be a function of range, terrain, environment and the tactical situation. In the case of suppressed sensors the replacement rate function could model their return to operational status. Both uses would require care in the implementation to insure that the forces did not inadvertently grow beyond their true size due to replacements.

2. Range Dependent Acquisition Coefficients

Just as attrition depends on the range separating the combatants, so does acquisition. For small changes in range the attrition (acquisition) coefficients may be relatively invariant. However, when range changes appreciably during the course of the battle the attrition (acquisition) coefficients should reflect this movement. Taylor [Ref. 9:pp. 54,55] reviewing research in the area due to Bonder, discusses the following functional form for range dependent attrition coefficients:

$$a(r) = \begin{cases} a_0[1 - (r/r_e)]^u & ,\text{for } 0 \le r \le = r_e \\[2mm] 0 & ,\text{for } r > r_e \end{cases} \qquad (4.45)$$

where

    $a(r)$ = a range dependent attrition coefficient

      a_0 = the maximum kill rate

      r_e = the maximum effective range of the weapon system

       r = the current separation range between the target and weapon

u = a shaping parameter used to adjust for the weapons systems
kill rate.

This functional form should be appropriate for modeling the range dependence of the target acquisition process. Additionally, by judicious choice of the shaping parameter, u, other variables such as terrain, environment and tactical situation may be included. One possibility is to make the shaping parameter, u, a function of the attenuation coefficient found in some target acquisition models. The U.S. Army's Night Vision and Electro-Optical Laboratories (NVEOL) has developed a target acquisition model for use in high resolution combat simulations. The NVEOL model allows for the attenuation of target signature due to range and atmospheric conditions which exist between the sensor and target.

3. Fraction of Force Which is Effective

Up to now it has been assumed that all the sensors of the scanning force are effective and can be concentrated on one sector. This generally is not the case. The scanning unit normally will maintain 360^0 surveillance of its area of responsibility. Depending upon the tactical situation, however, its attention may not be equally focused in all directions. The majority of its sensors may be pointed toward sectors along and adjacent to a principal direction of orientation. This will result in some sectors having few, if any, sensors covering them. Therefore, the rate at which targets are acquired may depend upon the angle between the scanning unit's principal direction of orientation and the target. Lanchester differential equations can be modified by including a factor for the fraction of the scanning force which is effective. For example, the rate at which the X force is acquired, based on the Second Linear Law becomes:

$$dX/dt = -af_e YX \qquad (4.47)$$

where

f_e = the fraction of the Y force scanning the sector(s) in which the X force is located.

Two simple models for determining the fraction of scanning forces which are effective are discussed below.

a. Circular Scanning

The assumption is that the scanning force does not have a principal direction of orientation, but rather scans all sectors in a 360^0 arc (at random) with equal intensity. This would result in a circular probability density function. The expected fraction of sensors (or time spent) searching a sector within which a target is located is simply:

$$1/(2\pi)\int_{\theta_1}^{\theta_2} dt \quad , 0 \leq \theta \leq 2\pi \tag{4.49}$$

where:

θ_1 = lower boundary of the search sector

θ_2 = upper boundary of the search sector .

A unit may use this type of scanning when it is isolated and is unable to establish physical contact with adjacent units or does not possess sufficient knowledge which would allow it to determine a principal direction of enemy attack. Examples are a small tactical unit conducting a reconnaissance patrol, a combat unit which has been cut off from other friendly units by an attacking enemy force, or a support unit in the rear area which is subject to harassing attacks from many directions.

b. Cardoid Scanning

An alternative model which may apply when the scanning unit concentrates its sensors into sectors along a principal direction of orientation is the cardoid probability density function displayed in Figure 4.1 The expected fraction of sensors (or time spent) searching a sector within which a target is located is:

$$1/(2\pi)\int_{\theta_1}^{\theta_2} (1+\cos\theta) \, d\theta \quad , 0 \leq \theta \leq 2\pi \tag{4.51}$$

where

θ_1,θ_2 are the angular limits of the search sector as measured from the principal direction of orientation.

The cardoid probability density function concentrates scanning around the the principal direction of orientation, $\theta = 0$. This would be a suitable model for the majority of tactical situations faced by a typical combat unit. In the attack a unit maintains 360^0 security (surveillance) but concentrates its search in the direction of the

attack. Similarly, in the defense, a unit is positioned to cover designated avenues of approach. The unit orients its search to cover this avenue of approach. It would also, however, position elements to provide the required all around security.
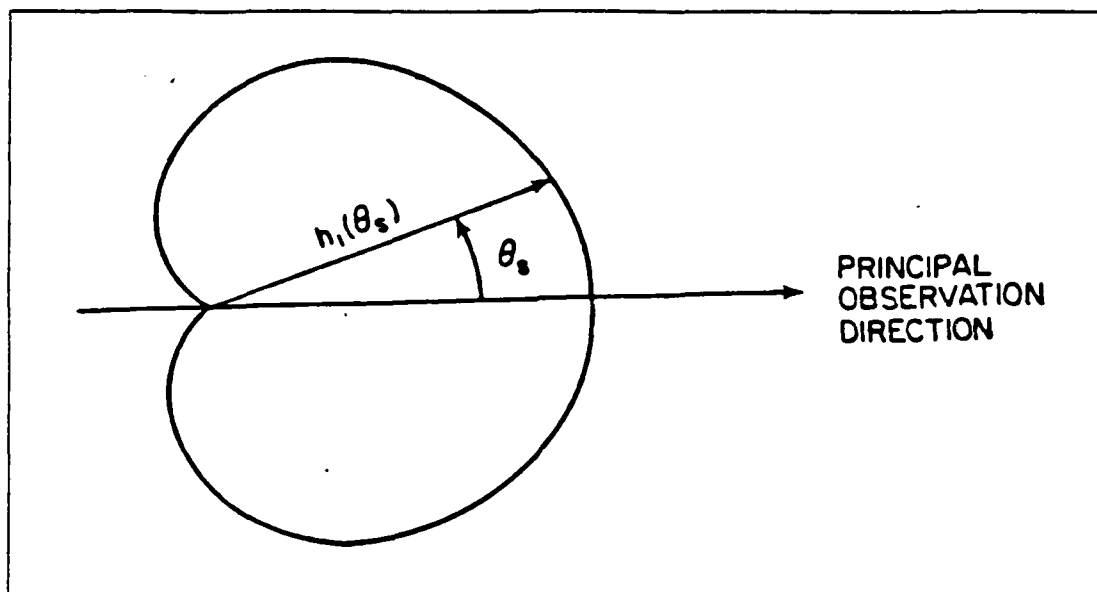

Figure 4.1   Cardoid Function.

One of the touted advantages of using Lanchester-type differential models is the ability to consider heterogeneous forces. These heterogeneous formulations are presented next.

F.   HETEROGENEOUS FORCES

Modern combat forces rarely fight as a pure (homogeneous) force. Rather, different systems (infantry, armor, artillery and aircraft) are integrated into a combined arms force which capitalizes on the unique strengths of each system. Lanchester's original differential models have been modified to consider combat between these combined arms (heterogeneous) forces. As an example consider a battle between two heterogeneous forces where the X force has "I" different type systems and the Y force has "J" different type systems. If attrition occurs according to the Square Law, the rates at which specific systems are attrited are given by:

$$dX_i/dt = -\sum_{j=1}^{J} a_{ji} g_{ji} Y_j \quad , i = 1,2,...,I \qquad (4.53)$$

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and

$$dY_j/dt = -\sum_{i=1}^{I} b_{ij}k_{ij}X_i \quad , j = 1,2,...,J \tag{4.55}$$

with

$$X_i(0) = X_{io} \text{ and } Y_j(0) = Y_{jo}$$

Where

X_i = remaining number of i-type X elements at time, t

Y_j = remaining number of j-type Y elements at time, t

a_{ji} = rate at which the jth type Y force system attrits one of the ith type system of force X

b_{ij} = rate at which the ith type X force system attrits one of the jth type system of force Y

g_{ji} = proportion (probability) that the jth type Y system engages the ith type X system, $0 \le g_{ji} \le 1.0$.

k_{ij} = proportion (probability) that the ith type X system engages the jth type Y system, $0 \le k_{ij} \le 1.0$.

X_{io} = initial number of i-type X systems

Y_{jo} = initial number of j-type Y systems.

(note: $\sum_{i=1}^{I} g_{ji} \le 1.0$ and $\sum_{j=1}^{J} k_{ij} \le 1.0$)

Similar heterogeneous formulations apply to the Linear Laws. As suggested previously with homogeneous attrition models, the heterogeneous formulations could be used to model target acquisition between opposing combined arms forces.

One of the difficulties that may arise in using heterogeneous formulations (both in attrition and acquisition models) is the problem of determining the allocation proportion coefficients for each opposing system combination. Some coefficients may be obvious, such as the proportion of anti-aircraft radar systems devoted to detecting approaching infantry. An example of a more subtle case, though, involves ground surveillance radars (GSR). These sensors are capable of detecting both motion and sound. Typically they are employed to cover large sectors and alert the unit to approaching enemy forces. They do not search exclusively for any specific type of

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enemy force, but rather search for both dismounted infantry and armored forces. To assign a proportion of the available GSR to detecting only a single type target would incorrectly degrade its performance against a combined arms force. A solution may be to estimate the acquisition coefficients from the output of a high resolution model. These estimated acquisition coefficients will reflect the rates at which each specific sensor-type acquires each target-type. The allocation proportion coefficients should be intrinsic to the estimated acquisition coefficients.

This thesis begs the question of how allocation proportion coefficients are finally determined. It is presumed that if the decision is made to use a heterogeneous Lanchester-type formulation to model target acquisition, follow-on studies will be conducted to resolve problems surrounding the assignment of the allocation coefficients. The next chapter presents a methodology by which acquisition coefficients can be estimated from the output of a high resolution combat simulation or field trial results.

V. DETERMINATION OF ACQUISITION COEFFICIENTS

A. THE ACQUISITION-RATE COEFFICIENT'S RELATIONSHIP TO ACQUISITION TIME

The basic Lanchester-type model of attrition is of the form:

$$dX/dt = -\alpha(t,X,Y)$$
$$dY/dt = -\beta(t,X,Y) .$$

In this case the attrition rate function, $\alpha(t,X,Y)$, may depend on time, the X force level and the Y force level. For example, using the square law formulation:

$$dX/dt = -aY$$
$$dY/dt = -bX$$

the attrition rate functions are:

$$\alpha(t,X,Y) = -aY$$

and

$$\beta(t,X,Y) = -bX$$

where a and b are the attrition rate coefficients.

Most current calculations of attrition rate coefficients are based on the premise that the coefficients are the reciprocal of the expected time for an individual firer to kill a single target. Therefore, when using a Lanchester-type model for acquisition it would seem reasonable to use the reciprocal of the expected time for a searcher to acquire a target as the acquisition coefficient. The Lanchester acquisition-rate coefficient is given by:

$$a = 1/E[T_{xy}] \tag{5.2}$$

where $E[*]$ is the mathematical expectation and T_{xy} is the time (a random variable) for a Y searcher to acquire an X target.

Using this definition, the determination of the expected time to acquire a target is the fundamental calculation required for arriving at the acquisition-rate coefficients in a Lanchester-type model.

B. JUSTIFICATION FOR USING THE RECIPROCAL OF THE TIME TO ACQUIRE

This justification follows an argument presented by Taylor [Ref. 10:pp. 397-437] concerning the use of the reciprocal of the expected time to kill a target as the attrition-rate coefficient in a homogeneous Lanchester-type combat model.

1. Acquisition as a Continuous Time Markov-Chain

Let acquisition be modelled as a continuous time Markov-Chain. The number of unacquired combatants on each side is a non-negative, integer random variable where:

m_0 = the initial number of X force combatants

n_0 = the initial number of Y force combatants

$M(t)$ = a random variable, the number of unacquired X force combatants at time t with realization denoted as m

$N(t)$ = a random variable, the number of unacquired Y force combatants at time t with realization denoted as n

$G(t,m,n)$ = the rate at which the X force is acquired

$H(t,m,n)$ = the rate at which the Y force is acquired

2. Development of The Forward Kolmogorov Equations

Let the individual component state probability vector be denoted as, $P(t,m,n)$, which is the probability that at time, t, the number of unacquired X force combatants is m and the number of unacquired Y force combatants is n given that at time, t = 0, the number of unacquired X force combatants was m_0 and the number of unacquired Y force combatants was n_0. Further assume that the probability that one X force combatant is acquired in the interval $[t,t+h]$ is:

$G(t,m,n) \times h$

and that the probability that one Y force combatant is acquired in the interval $[t,t+h]$ is:

$H(t,m,n) \times h$

and finally, the probability of a total of more than one acquisition on either one or both sides during the interval $[t,t+h]$ is:

$o(h)$

(a function $f(*)$ is $o(h)$ if $\lim_{h \to 0} f(h)/h = 0$).

The initial conditions for the forward Kolmogorov equations are:

$P(0,m,n) = 1$,for $m = m_0$ and $n = n_0$

$$P(0,m,n) = 0 \quad \text{,for } m \neq m_0 \text{ or } n \neq n_0$$

and

$$P(t,m,n) = 0 \quad \text{,for } m > m_0 \text{ or } n > n_0.$$

Now for $0 < m \leq m_0$ and $0 < n \leq n_0$

$$P(t+h,m,n) = P(t,m,n) \times \{1-[G(t,m,n) \times h + H(t,m,n) \times h]\}$$
$$+ P(t,m+1,n) \times G(t,m+1,n) \times h$$
$$+ P(t,m,n+1) \times H(t,m,n+1) \times h + o(h)$$

or since there is some probability that the state vector will be in the status, $M(t+h) = m$ and $N(t+h) = n$, then one of four mutually exclusive events must have occurred:

(1) $M(t) = m$ and $N(t) = n$ and there were no acquisitions during the interval $[t,t+h]$

(2) $M(t) = m+1$ and $N(t) = n$ and one X force combatant was acquired in the interval $[t,t+h]$.

(3) $M(t) = m$ and $N(t) = n+1$ and one Y force combatant was acquired in the interval $[t,t+h]$.

(4) two or more acquisitions took place during $[t,t+h]$.

Multiplying through and rearranging the term results in:

$$[P(t+h,m,n)\text{-}P(t,m,n)]/h = P(t,m+1,n) \times G(t,m+1,n)$$
$$+ P(t,m,n+1) \times H(t,m,n+1)$$
$$- P(t,m,n) \times G(t,m,n)$$
$$- P(t,m,n) \times H(t,m,n).$$

Taking the limit as $h \rightarrow 0$ results in the following:

$$dP(t,m,n)/dt = P(t,m+1,n)xG(t,m+1,n) + P(t,m,n+1)xH(t,m,n+1) \qquad (5.4)$$
$$-P(t,m,n)x[G(t,m,n) + H(t,m,n)]$$

Equation 5.4 is the forward Kolmogorov equation for the probability distribution of the number of unacquired combatants on both sides during the course of the battle. This equation applies only for the initial conditions given above. The Kolmogorov equations have a slightly different form at the boundaries. The full set of Kolmogorov equations is given by Taylor [Ref. 10:p. 408].

3. Distribution of Times Between Acquisitions

To determine the distribution of times between acquisitions the probability of no acquisitions in a time interval, $[0,t]$, is considered. For $m = m_0$ and $n = n_0$ then:

$$dP(t,m_0,n_0)/dt = -[G(t,m_0,n_0) + H(t,m_0,n_0)] \times P(t,m_0,n_0) \tag{5.6}$$

with the initial condition $P(0,m_0,n_0) = 1$.

This is an ordinary differential equation of the form:

$dP/dt + Q(t) \times P(t) = 0$ where

$Q(t) = G(t,m_0,n_0) + H(t,m_0,n_0)$

and with a solution given by:

$$P(t,m_0,n_0) = \exp\{-\int_0^t [G(s,m_0,n_0) + H(s,m_0,n_0)]\, ds\} \tag{5.8}$$

Now if T1 is the time at which the first acquisition occurs when measured from the beginning of the battle then:

$$\text{Prob}[T1 > t] = P(t,m_0,n_0) \tag{5.10}$$

which is the probability of no acquisitions in the interval, $[0,t]$. The distribution function, $F_{T1}(t)$, for the time to the first acquisition is given by:

$F_{T1}(t) = 1 - \text{Prob}[T1 > t]$ or

$$F_{T1}(t) = 1 - \exp\{-\int_0^t [G(s,m_0 n_0) + H(s,m_0,n_0)]\, ds\} \tag{5.12}$$

If the acquisition rate functions are independent of time then the acquisition process is a continuous-time Markov chain with stationary transition probabilities. The rate functions may be written as:

$G(t,m_0,n_0) = A(m_0,n_0)$

$H(t,m_0,n_0) = B(m_0,n_0)$

and then

$$F_{T1}(t) = 1 - \exp\{-[A(m_0,n_0) + B(m_0,n_0)] \times t\} \tag{5.14}$$

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Equation 5.14 can be recognized as the distribution function of an exponential probability density function with parameter:

$$\lambda = [A(m_0,n_0) + B(m_0,n_0)] \, .$$

Taylor [Ref. 10:p. 428] shows that this result can be generalized to any time interval, $[t, t+s]$, so that the time between acquisitions is given by the exponential density function:

$$f_S(s) = [A(m,n) + B(m,n)] \times \exp\{-[A(m,n) + B(m,n)]s\} \qquad (5.16)$$

where S = time between two successive acquisitions. The expected time between acquisitions is:

$$E[T_S] = 1/[A(m,n) + B(m,n)] \qquad (5.18)$$

Now, given that an acquisition has occurred the probability that an X force combatant was acquired is:

$$A(m,n)/[A(m,n) + B(m,n)]$$

and the probability that a Y force combatant was acquired is:

$$B(m,n)/[A(m,n) + B(m,n)]$$

Finally, given that at time, t, the Markov chain is in state, $M(t) = m$ and $N(t) = n$, then the probability that an acquisition occurs on or before time, $t + s$, and that an X force combatant is acquired is:

$$A(m,n)/[A(m,n) + B(m,n)] \int_0^s [A(m,n) + B(m,n)] \exp\{-[A(m,n) + B(m,n)]\tau\} \, d\tau$$

Similarly for a Y force acquisition:

$$B(m,n)/[A(m,n) + B(m,n)] \int_0^s [A(m,n) + B(m,n)] \exp\{-[A(m,n) + B(m,n)]\tau\} \, d\tau$$

The above results form the computational basis for determining the acquisition rates in a Lanchester-type model of acquisition. The next section discusses a procedure to estimate the acquisition rate coefficients from the output of high resolution simulations or field trials.

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C. MAXIMUM LIKELIHOOD ESTIMATION OF ACQUISITION-RATE COEFFICIENTS

The actual determination of numerical values for attrition coefficients has been accomplished by two approaches [Ref. 12:pp. 1,4]:

(1) A statistical estimate based on data generated by a detailed Monte-Carlo combat simulation.

(2) An analytical submodel of the attrition process.

This section presents a maximum likelihood estimation procedure for the acquisition coefficients of a Lanchester-type model of acquisition. It is based on the work done by Clark [Ref. 11] while developing his "Combat Analysis Model", COMAN, and presented by Taylor [Ref. 12:pp. 125,140]. The use of this procedure presupposes that data concerning the time between acquisitions is available from either a high resolution, Monte-Carlo simulation or field trials. This data is then used to compute statistical estimates of the acquisition-rate coefficients.

To illustrate the procedure the continuous-time Markov-chain analog of the deterministic, homogeneous, Lanchester square law will be used. Specifically let acquisition be modelled by:

$$dX/dt = -A(m,n) = -aY \quad \text{with } X(0) = X_0$$
$$dY/dt = -B(m,n) = -bX \quad \text{with } Y(0) = Y_0 \, .$$

where

a = number of X targets acquired/(Y observer × time)

b = number of Y targets acquired/(X observer × time)

Assume that a high resolution, Monte-Carlo simulation has been run until K acquisitions have occurred and that the time between successive acquisitions of X force and Y force combatants has been recorded. The time of the kth acquisition (for k = 1,2,...,K) will be a random variable, T_k, with realization t_k. Starting the battle at $t = 0$ the total length of the battle will be T_K. Then using the corresponding continuous-time Markov-chain model and the notation previously defined, let :

m_k = the number of unacquired X force combatants just after the occurrence of the kth acquisition

n_k = the number of unacquired Y force combatants just after the occurrence of the kth acquisition

S = time between consecutive acquisitions (a random variable) with realization denoted as s

C^x_k = 1 if the kth acquisition is an X force combatant and 0 otherwise

C^y_k = 1 if the kth acquisition is a Y force combatant and 0 otherwise

$$C^x_t = \sum_{k=1}^{K} C^x_k$$

$$C^y_t = \sum_{k=1}^{K} C^y_k$$

Note that

$$C^x_k \times C^y_k = 0$$

$$C^x_k + C^y_k = 1$$

and

$$C^x_t + C^y_t = K .$$

From the continuous-time Markov-chain model developed in the preceding sections Taylor [Ref. 12:pp. 130,131] shows that the time between acquisitions is an exponentially distributed random variable with density function given by:

$$f_S(s) = (an + bm) \times \exp[-(an + bm)s] \tag{5.20}$$

The maximum likelihood function for the sequence of acquisitions is the product of each of the individual components. For the kth acquisition the individual contribution for the acquisition of an X force combatant is:

$$(an_{k-1}) \exp[-(an_{k-1} + bm_{k-1})(t_k - t_{k-1})]$$

The contribution for the acquisition of a Y force combatant is:

$$(bm_{k-1}) \exp[-(an_{k-1} + bm_{k-1})(t_k - t_{k-1})]$$

Combining the two components and using the indicator variables results in:

$$(an_{k-1})^{C^x_k}(bm_{k-1})^{C^y_k}\exp[-(an_{k-1} + bm_{k-1})(t_k - t_{k-1})]$$

Therefore the likelihood function is given by:

$$L(a,b) = \prod_{k=1}^{K}(an_{k-1})^{C_k^x}(bm_{k-1})^{C_k^y}\exp[-(an_{k-1}+bm_{k-1})(t_k-t_{k-1})] \qquad (5.22)$$

Taking the natural logarithm of the likelihood function and maximizing it with respect to the parameters, a and b, results in the following estimators for the square law formulation:

$$\hat{a} = C^x{}_t / [\sum_{k=1}^{K} n_{k-1}(t_k - t_{k-1})] \qquad (5.24)$$

$$\hat{b} = C^y{}_t / [\sum_{k=1}^{K} m_{k-1}(t_k - t_{k-1})] \qquad (5.26)$$

These coefficients are the ratio of the total number of acquisitions of the combatants on one side to the total number of acquisition time units directed against that force by the opposing side. Thus the dimensions of the coefficients are acquisitions per time.

Taylor [Ref. 12:pp. 136,138] shows that this result is a special case and may be generalized. When the rate functions are of the form:

$$A(m,n) = a \times g_a(m,n) \qquad (5.28)$$

$$B(m,n) = b \times g_b(m,n) \qquad (5.30)$$

where

a and b are acquisition coefficients

and

$g_a(m,n)$ and $g_b(m,n)$ are functions which depend only on the state that the Markov process is in (i.e. they are independent of time)

the estimators are then given by:

$$\hat{a} = C^x{}_t / [\sum_{k=1}^{K} g_a(m_{k-1},n_{k-1})(t_k - t_{k-1})] \qquad (5.32)$$

$$\hat{b} = C^y{}_t / [\sum_{k=1}^{K} g_b(m_{k-1},n_{k-1})(t_k - t_{k-1})] \qquad (5.34)$$

The maximum likelihood estimation method was illustrated for homogeneous forces. Its applicability also extends to heterogeneous forces without extensive modification. The estimated parameters are those for acquisition of the ith type X combatant by the jth type Y combatant and vice versa. This requires detailed data on the successive acquisition times for all types of combatants on one side by all types of combatants on the opposing side. The result will be a set of estimated parameters $a_{i,j}$ and $b_{j,i}$ for all (i,j) and (j,i) pairs .

These coefficients will depend upon the rate by which specific target types are acquired by each sensor type in the high resolution model. Thus the allocation proportion coefficients of a heterogeneous Lanchester-type formulation are contained in the acquisition coefficients which have been estimated from a high resolution combat simulation.

D.   THE RATE AT WHICH ACQUIRED AN ACQUIRED TARGET RETURNS TO THE UNACQUIRED STATE

One of the fundamental differences between the attrition and acquisition processes is the regeneration of targets. In attrition models a destroyed target is permanently eliminated from the battlefield (this excludes those targets which are subsequently repaired and return to the battle). The acquisition process differs significantly in this respect; a target may make multiple shifts between the acquired and unacquired states during the course of the battle. An acquisition model based on a Lanchester-type formulation could account for this phenomenon by including a "replacement" coefficient. The basic Lanchester formulation for acquisition which includes targets returning to the unacquired state would have the form:

$$dX/dt = -\alpha(t,X,Y) + \kappa(t,X,Y)$$
and
$$dY/dt = -\beta(t,X,Y) + \lambda(t,X,Y)$$

where $\kappa(t,X,Y)$ and $\lambda(t,X,Y)$ are the acquisition-loss functions and measure the respective rates at which the X and Y forces return to the unacquired state.

In order to determine the rate at which combatants revert to the unacquired state the factors which cause the loss of acquisition must be determined. These factors can be grouped into three general categories.

- Physical - acquisition is lost due factors such as violation of range thresholds (the target moves beyond maximum range or closes to under minimum range), loss of line of sight, the cessation of the signature required for continued acquisition, etc.

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- Attrition - either the target is destroyed or the sensor(s) responsible for its continued acquisition is destroyed. In the first case the target is, in effect, removed from the battlefield and the population of combatants which are available to be acquired is reduced. The second case removes the sensor, however, the target may subsequently be re-acquired by the remaining sensors.

- Time - the failure to take timely action against a target or to re-confirmed the acquisition of a target may cause the loss of acquisition. As an example, field artillery units generally consider a target to be acquired even if a sensor is not currently monitoring the target. If, however, the targeting information is not acted upon or the acquisition re-confirmed within a reasonable period of time, the target is considered lost. It is as if the sensor "forgets" that it has acquired the target.

The rate at which targets return to the unacquired state would be a function of the above factors and would have individual components comprised of each. By modifying a high resolution combat simulation, such as the Simulation of Tactical Alternative Responses, (STAR), so as to maintain a record of targets returning to the unacquired state, it would be possible to obtain a numerical estimate for the values of the individual components. The acquisition-loss coefficient could in-turn be obtained from the individual components. This would allow the use of a Lanchester-type formulation to model acquisition in a large scale combat simulation like ALARM.

E. SUMMARY

This chapter has shown that the reciprocal of the expected time to acquire targets is a reasonable choice for the acquisition coefficients of a Lanchester-type formulation of acquisition in a large scale combat model. Further, numerical estimates of acquisition coefficients can be arrived at by the method of maximum-likelihood estimation. The ability to arrive at estimates of acquisition coefficients based on data generated from high resolution, Monte-Carlo simulations, in which established target detection models are used, is an important result. Additionally the same technique can be employed to obtain the acquisition-loss coefficients. The successful implementation of these techniques will be required in order to use a Lanchester-type formulation for target acquisition in ALARM.

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VI. THE INTELLIGENCE MODULE AND DECISION-MAKING IN ALARM

A. A. DECISION-MAKING IN ALARM

The preceding chapters of this thesis have concentrated on developing the conceptual basis for the Intelligence Module and the related function of target acquisition. The key to the decision making process in ALARM is the inter-relationships between the Execution, Planning and Intelligence Modules. This chapter illustrates the relationships between the modules by presenting an extended, worked example.

ALARM will use an approach to decision-making which has been referred to by Kilmer [Ref. 3:p. 11] as "future state decision making" as opposed to "current state decision making". Current state decision-making focuses on deciding at time, t_i, what actions should be taken at time, $t_i + t$, based on the perceived situation at t_i. Future state decision-making, as an alternative, uses the expected situation at time, $t_i + t$, as the basis for current decisions. This approach requires algorithms to predict the future states based on the situation at time, t, and to forecast how the situation will change over time. Kilmer has developed a set of exponential functions known as the Generalized Value System, GVS, which will be used to represent the future states of battlefield entities in ALARM. The GVS methodology is based on two major premises:

- The value of an entity at a particular point in time to a given hierarchical level is dependent on how useful the entity is at that time and on the availability of the entity. Power is the measure of that usefulness. The metric for power in GVS is called Standard Power Units (STAPOWS).

- The power of an entity that is not ready to execute its assigned mission is discounted. As the entity moves closer in time to being able to accomplish the assigned mission its power grows exponentially.

An entity's power is situational and may be classified as:

- Basic Inherent Power (BIP) - the inherent power possessed by an entity at full strength when it is in position to engage its most likely opponent.

- Adjusted Basic Inherent Power (ABIP) - the BIP of an entity adjusted for the specific mission and condition of the entity at the present time, t_p.

- Predicted Adjusted Inherent Power (PABIP) - the ABIP that an entity is predicted to have at time, t_i, given its current state at time, t_p, where $t_i \geq t_p$.

The PABIP for an entity is calculated using:

$$PABIP(t_i | t_p) = ABIP(t_p) \times \exp[-L(t_i - t_p)] \tag{6.2}$$

where L is assumed to be constant during the period (t_p, t_i).

- Situational Inherent power (SIP) - the PABIP of an entity which is adjusted for availability. For times before an entity is in available to perform its mission it is the PABIP discounted by an exponential factor. For times after the entity is in position to accomplish its mission it is the PABIP adjusted for attrition, if required.

The results of the SIP calculations and the graphs of the SIP curves, which reflect the predicted power of the entities involved in the battle, are the primary devices used for future state decision-making as presented in this worked example. In order to maintain simplicity several assumptions will be made.

- The time used in the example is the simulation clock time and is measured in hours from $t = 0$. It will advance in 1 hour steps.
- When a unit is moving its rate of advance is constant. This allows simulation time to be used in the formulas for determining power.
- Units lose power according to the situation based on the following rate schedule:
  - a. 0.0 per hour for stationary units not engaged in combat with enemy forces.
  - b. .05 per hour for units which are moving but not engaged in combat with enemy forces.
  - c. .10 per hour × the number of enemy units which are being fought for units which are engaged in combat.

A unit's power at any given time can be found by using:

$$Power(t) = Power(t_i) \times \exp[L(t - t_i)] \tag{6.4}$$

where L is the the natural logarithm of (1.0 - the loss rate) and $t \geq t_i$.

For example a unit with an initial power $= 100$, at $t_o = 0$, moves for three hours unopposed and then engages in combat with two enemy units for one hour. The loss of power is:

power $= 100 \times \exp[(\ln.95) \times 3] = 85.74$, for $t = 3$ and

power $= 85.74 \times \exp[(\ln.80) \times 1] = 68.59$, for $t = 4$.

- Only ground maneuver units can engage more than one enemy unit simultaneously. Artillery and attack helicopter units can only engage one enemy unit at a time.
- There are no synergistic effects as a function of force mix. The power of a composite unit is merely the sum of the power of each individual component unit.
- Individual units cannot be split. They must be assigned as a whole to a single mission.
- Intelligence about enemy activities held by senior units will only be made available to a subordinate when the enemy unit crosses into the subordinates area of interest. Information on enemy units outside of a unit's area of interest cannot be obtained.

Since the purpose of this example is to illustrate the logical relationships between the Intelligence, Execution and Planning Modules certain functions of each will be treated as "black boxes". Only the **results** of target acquisition, attrition and movement, which are accomplished in the Execution Module, will be reported. Similarly, the decisions reached in the Planning Module will be implemented without detailing the methodology by which they were reached. The algorithms by which the intelligence estimates are arrived at has not been developed. As a consequence predicted enemy courses of action, which would be generated within the IEP of the Intelligence Module, are also presented without detailing the actual process.

Finally, as a disclaimer, this example does not preport to reflect correct tactical doctrine, rather it is contrived in order to present various functions of the Intelligence Module.

B. A WORKED EXAMPLE

The example will concentrate of the flow of information and the subsequent decisions within a Blue Armored Brigade.

1. Scenario

A Blue Armored Brigade is defending an area against an approaching Red Motorized Rifle Division. The mission of the Blue forces is to prevent the Red forces from advancing past the rear boundary of the Brigade for the next 12 hours. The combat entities involved in the battle along with their ABIPs are given in Table 5. The ABIPs of the Blue forces reflect that they are being employed in a defensive operation. The advantage accruing to a defending unit is assumed to triple its BIP. A diagram of the battlefield, showing the Areas of Interest and Influence, is at Figure 6.1. A cartesian coordinate system is used for reporting and example calculations.

TABLE 5
INITIAL ABIP OF COMBAT UNITS

ENTITY	TYPE	ABIP
X1	Tank Battalion	3000
X2	Tank Battalion	3000
X3	Tank Battalion	1000
X4	Attack Heli. Co.	2400
X5	Field Artillery Btry.	1800
Y1	Motorized Rifle Reg.	2100
Y2	Motorized Rifle Reg.	2100
Y3	Motorized Rifle Reg.	3000
Y4	Tank Regiment	3600

2. Initial Situation, t = 0

The position of the forces at time, $t_i = 0$, is shown in Figure 6.2a. Red Regiments Y1 and Y2 have just finished fighting the Blue Divisions covering force and are in the process of resupplying and reorganizing. Red Regiments Y3 and Y4 are about to enter the Blue Brigade's area of interest. The Red plan calls for Y3 to conduct a supporting attack in Blue sector 1 at t = 3 while Y4 attacks in Blue sector 2 at t = 2 . After resupplying Y1 and Y2 will also attack in sector 2 at t = 4 in an attempt to overwhelm the defending forces (the attack time is the time at which the attacking force reaches the Blue Brigade's area of influence).

The Blue Brigade has deployed its subordinate units so that X1 is defending in sector 1 and X2 is defending in sector 2. X3 is the Brigade's reserve and is positioned so that it can move to reinforce either X1 or X2 within one hour. The initial Blue plan
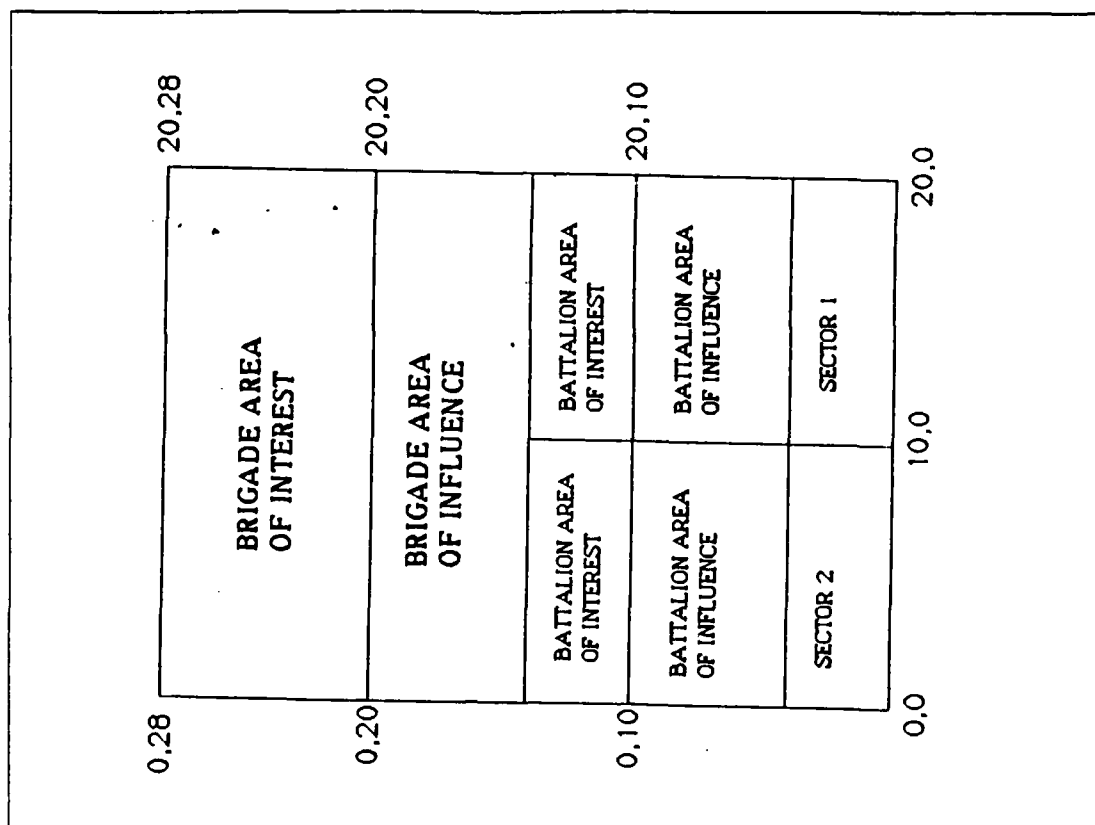
Figure 6.1   Diagram of Battlefield.

calls for X4, the attack helicopter company, to support X1 while X5, the artillery battery, will be used to support X2. Plots of the true projected SIP curves for the initial plans of both forces are shown in Figure 6.3. The plots are presented for the Brigade sector as a whole (Figure 6.3a) and for sectors 1 and 2 separately (Figure 6.3b and c respectively). Notice that overall the Brigade has the needed combat power to defeat the Red forces, however, the initial Blue plan does not correctly assign the subordinate units. Specifically sector 2 does not possess adequate combat power to successfully oppose the attacking Red forces.

In accordance with the assumptions the Blue Brigade's knowledge about the Red forces is limited to Y1 and Y2 which are located within its area of interest. For the purposes of this example a shortened version of the target vector, which was introduced in Chapter III, will be used to present the Blue Brigade's perception of the Red forces. Specifically the following components will be used:
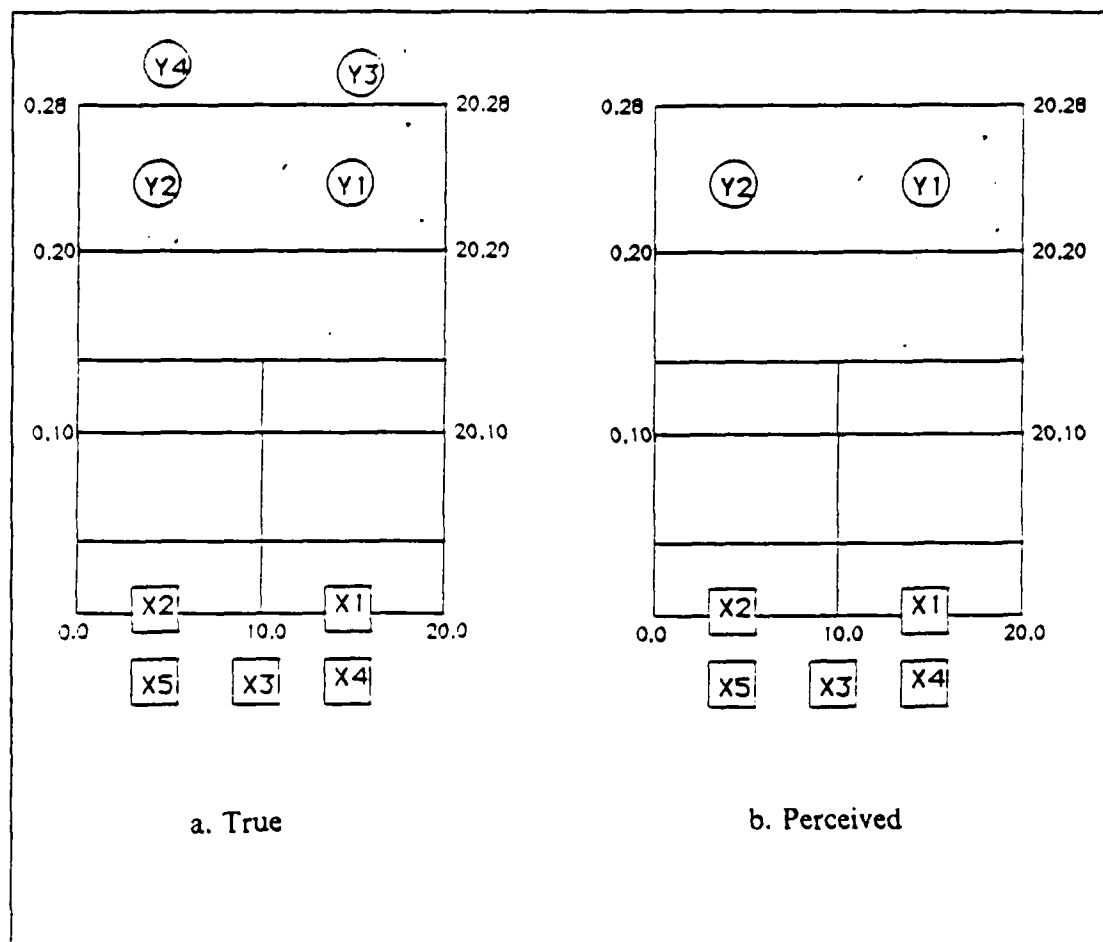
- I_1 = targets true identity

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Figure 6.2   Situation At t = 0.

- I_2 = assigned target number
- T = perceived type of unit ,where T = tank and M = motorized
- S = number of acquired primary fighting vehicles
- Y = perceived ABIP
- A = perceived activity, where A = attacking, M = moving and S = stationary
- L_x, L_y = projected location at the next time step based on the perceived current activity (given in cartesian coordinates)

For the initial situation the target vectors are:

(Y1,1,M,70,2100,S,15,25)

(Y2,2,M,70,2100,S,05,25)

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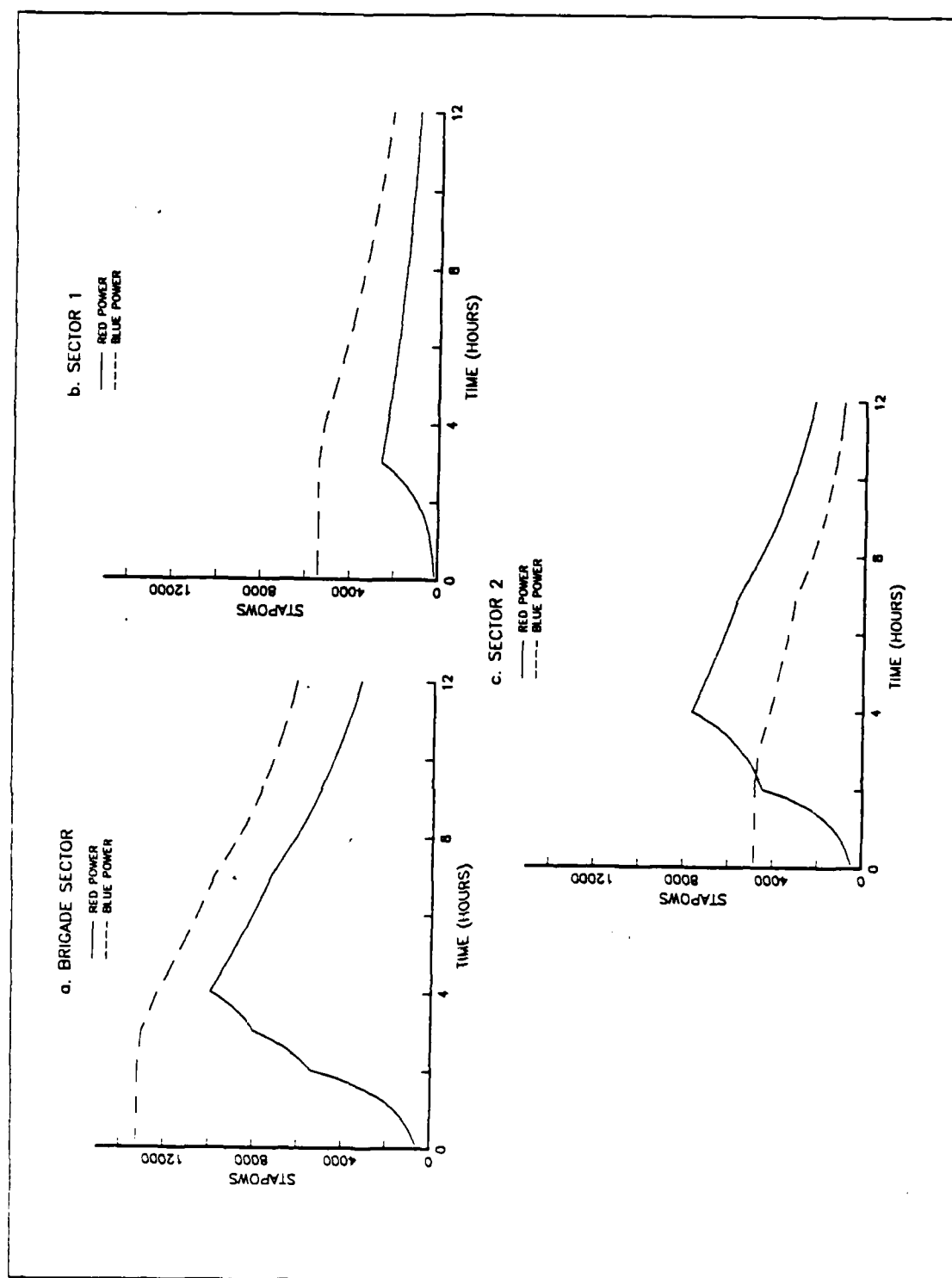
Figure 6.3 Projected Power Curves for Initial Plans.

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Blue intelligence estimates that Y1 and Y2 will not be completed resupplying before t = 3 and that they will attack in sectors 1 and 2, respectively, at t = 4. The Blue perception of the battlefield at t = 0 is shown in Figure 6.2b. The associated SIP curves are displayed in Figure 6.4. Based on the these power curves the Planning Module determines that the currently assigned forces can defeat the projected attacks in each sector.

3. Situation at t = 1

The position of the forces at time, t = 1, is shown in Figure 6.5a. Red Regiments Y1 and Y2 are continuing to resupply . Red Regiments Y3 and Y4 have entered the Blue Brigade's area of interest and are advancing to attack in accordance with the initial Red plan.

The Blue Brigade's CIP has received the following information vectors from the Execution Module:

$$(Y1,M,70,S,15,25)$$
$$(Y2,M,70,S,05,25)$$
$$(Y3,M,20,M,14,24)$$
$$(Y4,T,30,M,06,24)$$

The information vector is a subset of the target information vector components where:

- I_I = targets true identity
- T = type of unit
- S = size of unit
- A = activity
- L_x and L_y = the reported location in cartesian coordinates .

Following the flow diagram for target aggregation (Figure 3.2) the CIP sequentially processes each information vector and aggregates or creates new target vectors as required. For the purposes of the example a standard Red regiment will have 100 primary fighting vehicles. The circular error probable (CEP) associated with the Blue Brigade's ability to locate a Red regiment is 1.774 and is assumed to be proportional to the number Red vehicles where:

$$CEP = 0.01774 \times S .$$

For brevity, only the aggregation tests will be shown for the information vectors concerning Y3 and Y4 . The level of significance will be set for α = 0.05; the 95th quantile of the χ_2^2 distribution is 5.991.
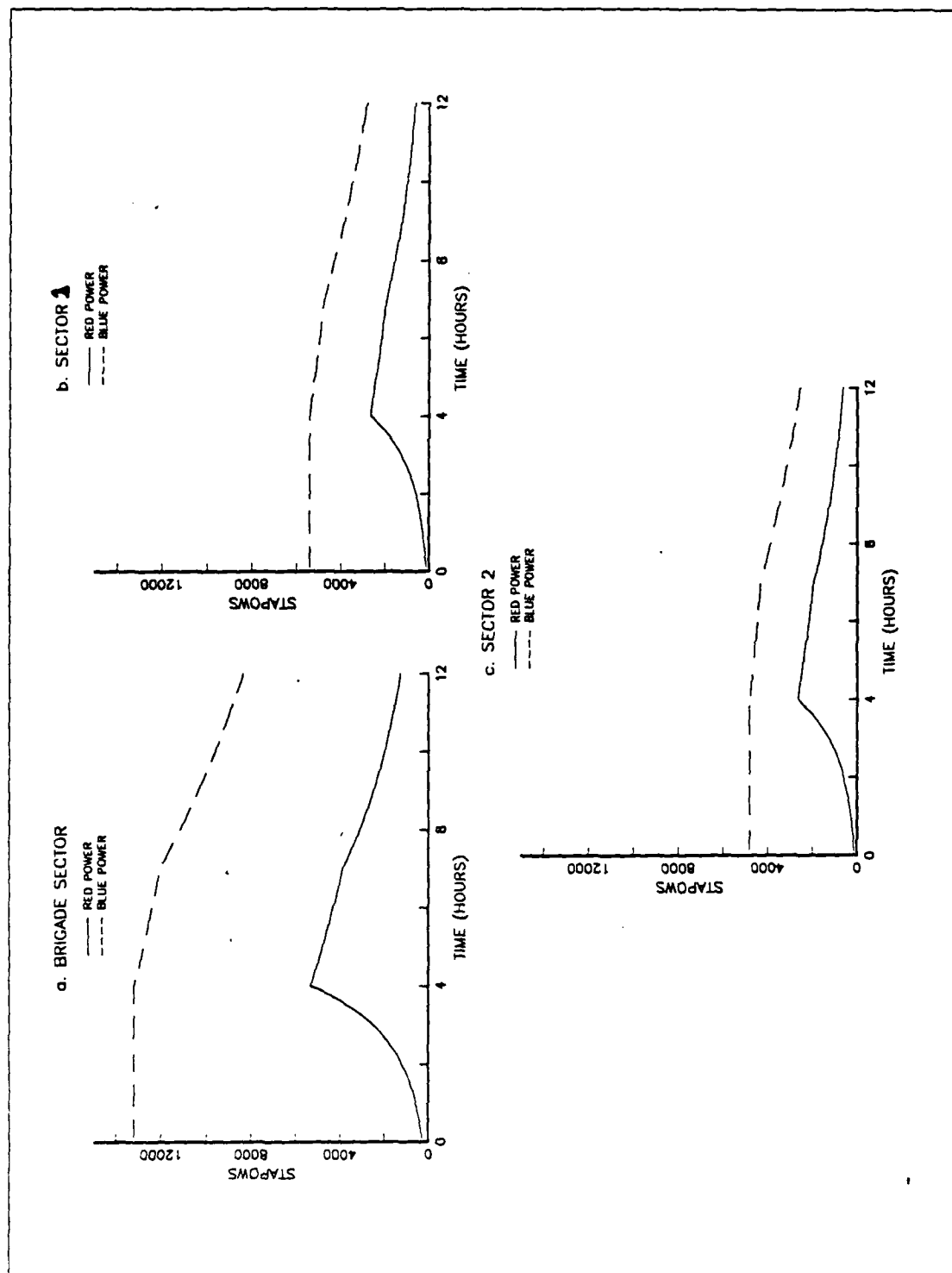
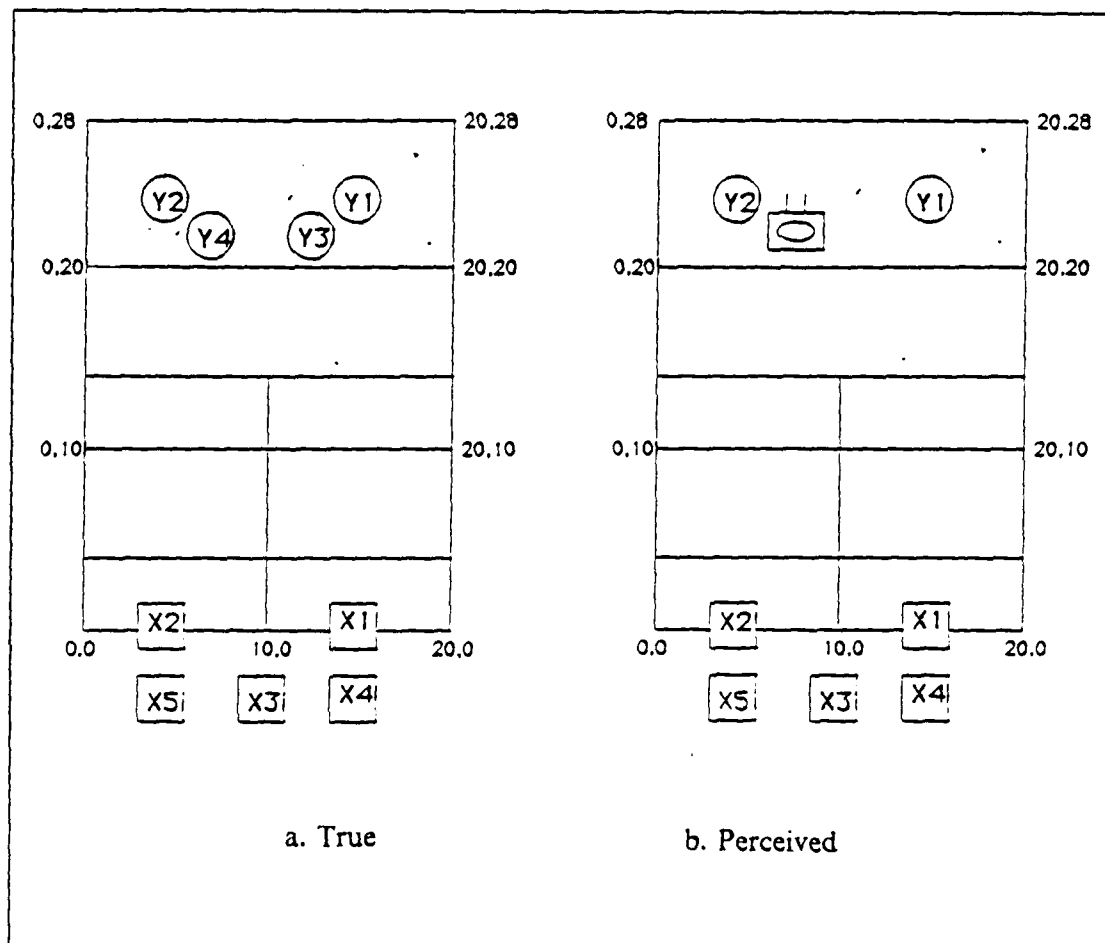76

Figure 6.4 Perceived Power Curves For t = 0.

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Figure 6.5   Situation at t = 1.

a. Tests on Information Vector Y3.

    (1) Type test - a search of the current target vectors reveals a type match with target 1.

    (2) Proximity test

$$D^2 = (15-14)^2 + (25-24)^2 = 2.0$$
$$\sigma_i^2 = (1.2418/1.774)^2 = 0.49$$
$$\sigma_2^2 = (0.3548/1.774)^2 = 0.04$$
so
$$T = 2.0/(0.49 + 0.04) = 3.77$$

For an $\alpha = .05$ the null hypothesis cannot be rejected. The information vector is judged to be a separate report about target 1.

    (3) Adjusted Location - the adjusted location of target 1 is calculated

using:

$r_1 = 70/(70 + 20) = 0.78$

$r_2 = 20/(70 + 20) = 0.22$

$s_1 = 0.7/(0.7 + 0.2) = 0.78$

$s_2 = 0.2/(0.7 + 0.2) = 0.22$

so

$X' = [15 \times (0.78 + 0.22)/2 + 14 \times (0.22 + 0.78)/2] = 14.5$

$Y' = [25 \times (0.78 + 0.22)/2 + 24 \times (0.22 + 0.78)/2] = 24.5$

The intermediate target vector is:

(Y1,1,M,70,*,S,14.5,24.5) .

This intermediate target vector is passed to the IEP which predicts the probable course of action of the enemy unit. Based on this the ABIP and the next position of the unit are estimated. The final target vector is:

(Y1,1,M,70,2100,S,14.5,24.5)

b. Tests on Information Vector Y4.

A search of the current target vectors fails to reveal a type match with information vector Y4. A new intermediate target vector is created and passed to the IEP which returns the final target vector:

(Y4,3,T,30,1000,M,10,17)

This new combat information is reported to the division CIP. The final result of the target aggregation process is the set of three target vectors:

(Y1,1,M,70,2100,S,14.5,24.5)

(Y2,2,M,70,2100,S,05,25)

(Y4,3,T,30,1000,M,10,17)

which represent the Blue Brigade's perception of the battlefield.

Using these target vectors the IEP concludes that the new target is a tank battalion which will be used to locate the defending Blue forces in sector 2 and initiate the attack; Y2 will follow Y4 and attempt to break-through. The perceived situation is shown in Figure 6.5b and the corresponding SIP curves in Figure 6.6. Based on the perceived situation there has been a slight increase in the threat to the Brigade. However, there still appears to be no difficultly in dealing with the attacks by using the initial Brigade plan. No changes are ordered by the Planning Module.
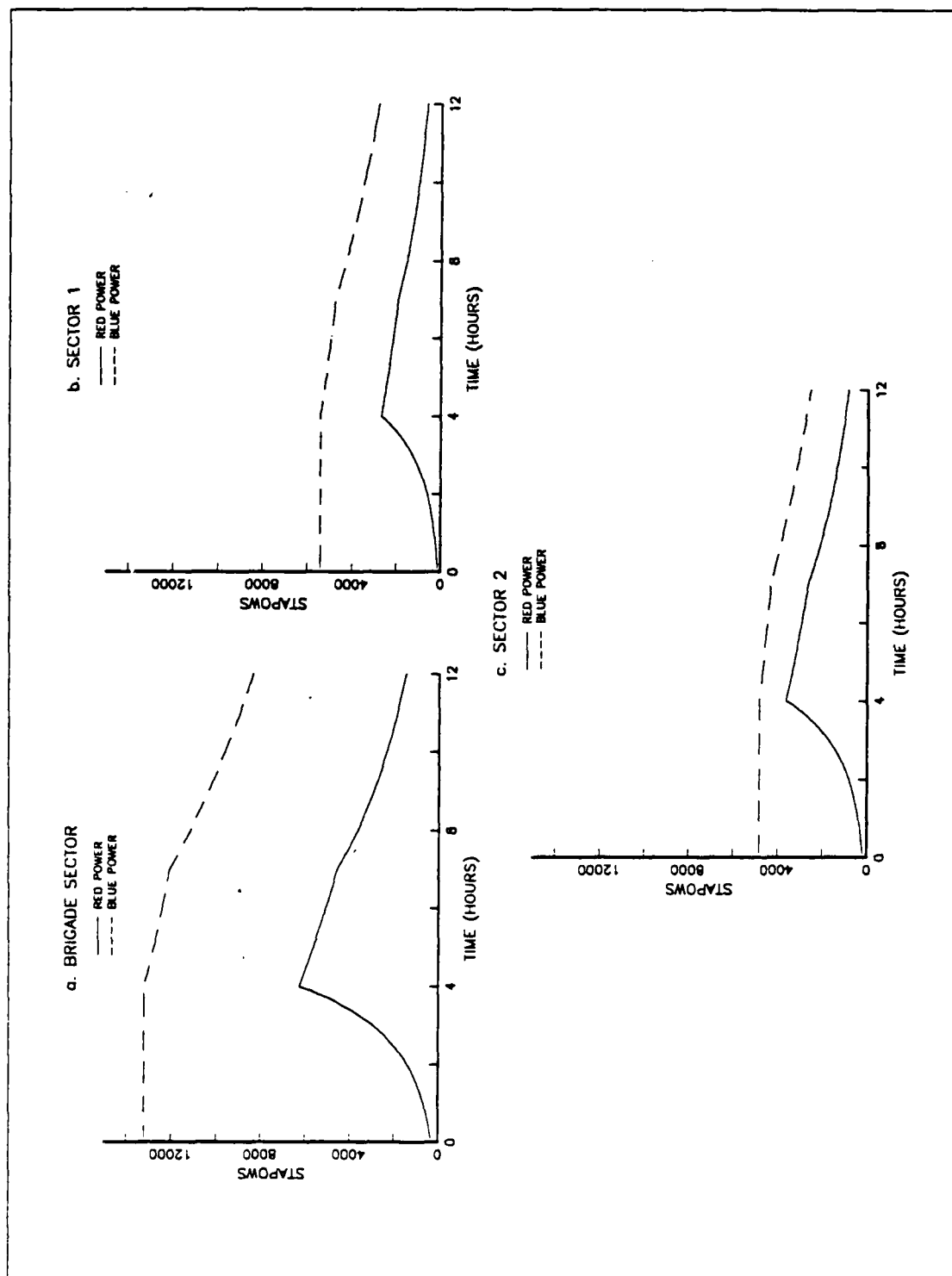
Figure 6.6   Perceived Power Curves for t = 1.

4. Situation at t = 2

The position of the forces at time, t = 2, is shown in Figure 6.7a.. Red Regiments Y1 and Y2 are continuing to resupply . Red Regiments Y3 and Y4 have entered the Blue Brigade's area of influence and are advancing to attack in accordance with the initial Red plan.
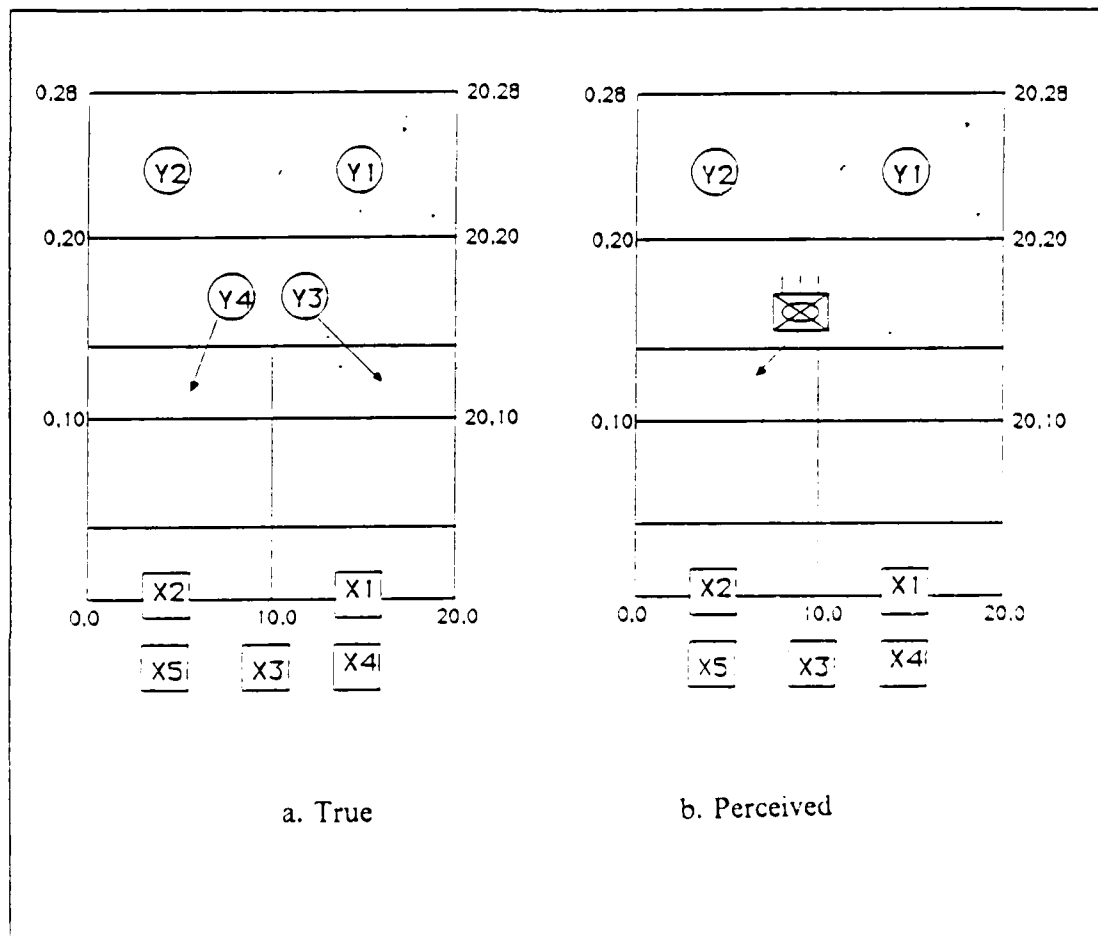

Figure 6.7   Situation at t = 2.

The Blue Brigade's CIP has received the following information vectors from the Execution Module.

$$(Y1,M,70,S,15,25)$$
$$(Y2,M,70,S,05,25)$$
$$(Y3,M,30,A,12,18)$$
$$(Y4,T,60,A,09,17) .$$

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Again, considering only the information vectors for Y3 and Y4, the the target aggregation procedure is initiated by the CIP. Based on the type test Y3 is tested for proximity to target vector 1, the closest similar type unit. This produces a test statistic of T = 94.47, which results in the rejection of the null hypothesis and the creation of the following intermediate target vector

$$(Y3,4,M,30,*,A,12,18) \, .$$

Similarly a type test for Y4 matches it to target vector 3. The proximity test, which compares the reported location of Y4 to the estimated location of target 3, returns a test statistic of T = 2.78, which does not allow the the null hypothesis to be rejected. The existing target vector 3 is updated to reflect the new combat information. The intermediate target vector is:

$$(Y4,3,T,*,A,09,17) \, .$$

These intermediate target vectors are processed by IEP which returns the following full set of target vectors which now include the estimated power and next location of the enemy units

$$(Y1,1,M,70,2100,S,15,25)$$
$$(Y2,2,M,70,2100,S,05,25)$$
$$(Y4,3,T,60,2500,A,05,06)$$
$$(Y3,4,M,30,1000,A,07,07).$$

This new set of target vectors reflect the IEP estimate that target 3 consists of two tank battalions while target 4 is a motorized rifle battalion. It concluded that Y3 and Y4 will attack in sector 2. There is no change in the forecasted activities of Y1 and Y2. Based on the SIP curves generated by the IEP, the Planning Module uses X5, the artillery battery, to place long range fires on Y4. The combat information about Y3 and Y4 along with the notification of the initiation of combat action against Y4 is sent to the division CIP. The Blue Brigade's perception of the battlefield is displayed in Figure 6.7b.

The SIP curves, which have been adjusted to reflect the use of X5, are shown in Figure 6.8. Notice that overall the Blue Brigade perceives that it holds a decided advantage. However, within sector 2 the attacking Red forces will achieve a slight advantage just before t = 4 which they will maintain throughout the duration of the battle. The advantage is judged not to be significant and no additional Blue forces are committed to the sector.
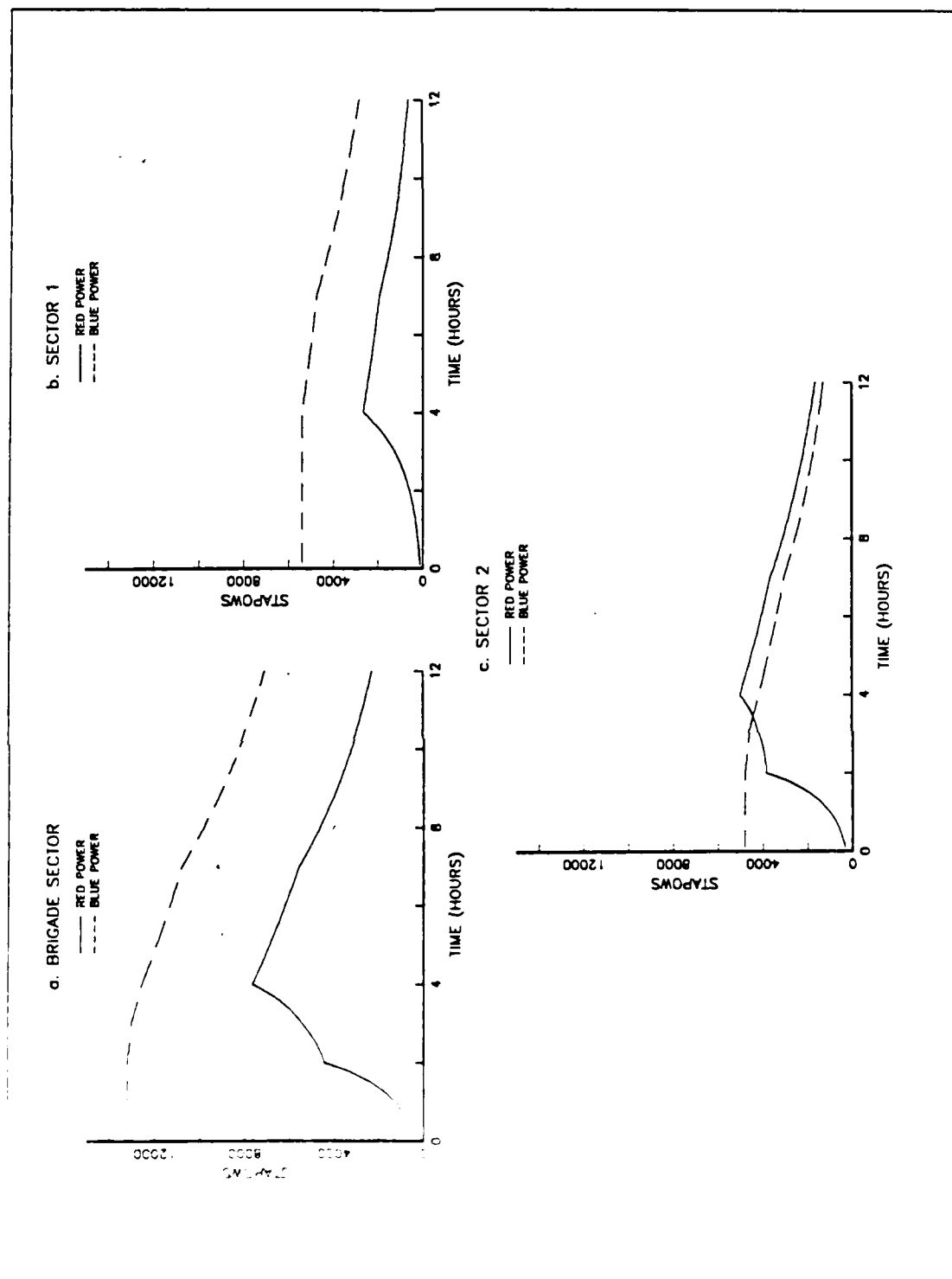
Figure 6.8 Perceived Power Curves For t = 2

5. Situation at t = 3

The position of the forces at time, t = 3, is shown in Figure 6.9a. Red Regiments Y1 and Y2 have completed resupplying and are moving to the attack. Red Regiment Y3 has entered the battalion area of interest for sector 1 while Y4 has entered the area of influence for the battalion in sector 2. Y4 is still under attack by X5 and has been automatically engaged by X2 when its area of influence was entered.

The Blue Brigade's CIP has received the following information vectors from the Execution Module.

$$(Y1,M,80,M,15,25)$$
$$(Y2,M,80,M,05,25)$$
$$(Y3,M,90,A,15,12)$$
$$(Y4,T,90,A,05,07) \, .$$

The CIP conducts the target aggregation tests which results in the following intermediate target vectors

$$(Y1,1,M,80,*,S,15,25)$$
$$(Y2,2,M,80,*,S,05,25)$$
$$(Y4,3,T,90,*,A,05,07)$$
$$(Y3,4,M,90,*,A,15,12) \, .$$

Using this set of target vectors the IEP estimates that Y4 is a tank regiment and Y3 is a motorized rifle regiment. The predicted course of action for the Red forces has Y3 attacking in sector 1 and supported by Y1 which will arrive at t = 4. Y4 is attacking in sector 2 and will be supported by Y2 which is projected to enter the battle at t = 4. The IEP adjusted target vectors are:

$$(Y1,1,M,80,2400,M,15,15)$$
$$(Y2,2,M,80,2400,M,05,15)$$
$$(Y4,3,T,90,3300,A,05,07)$$
$$(Y3,4,M,90,2700,A,15,07).$$

The updated combat information on Y3 and Y4 is send to the division CIP. Additionally the CIP of X1 is notified of the arrival Y3 within its area of interest. The perceived battlefield situation is shown in Figure 6.9b.

The Planning Module orders X4, the attack helicopter company, to engage Y3 The perceived SIP curves which result from these modifications in the Blue plan are it Figure 6 10 The Blue Brigade still believes that it holds an overall advantage for the Brigade sector as a whole. The projected power of the Red forces in sector 1 has
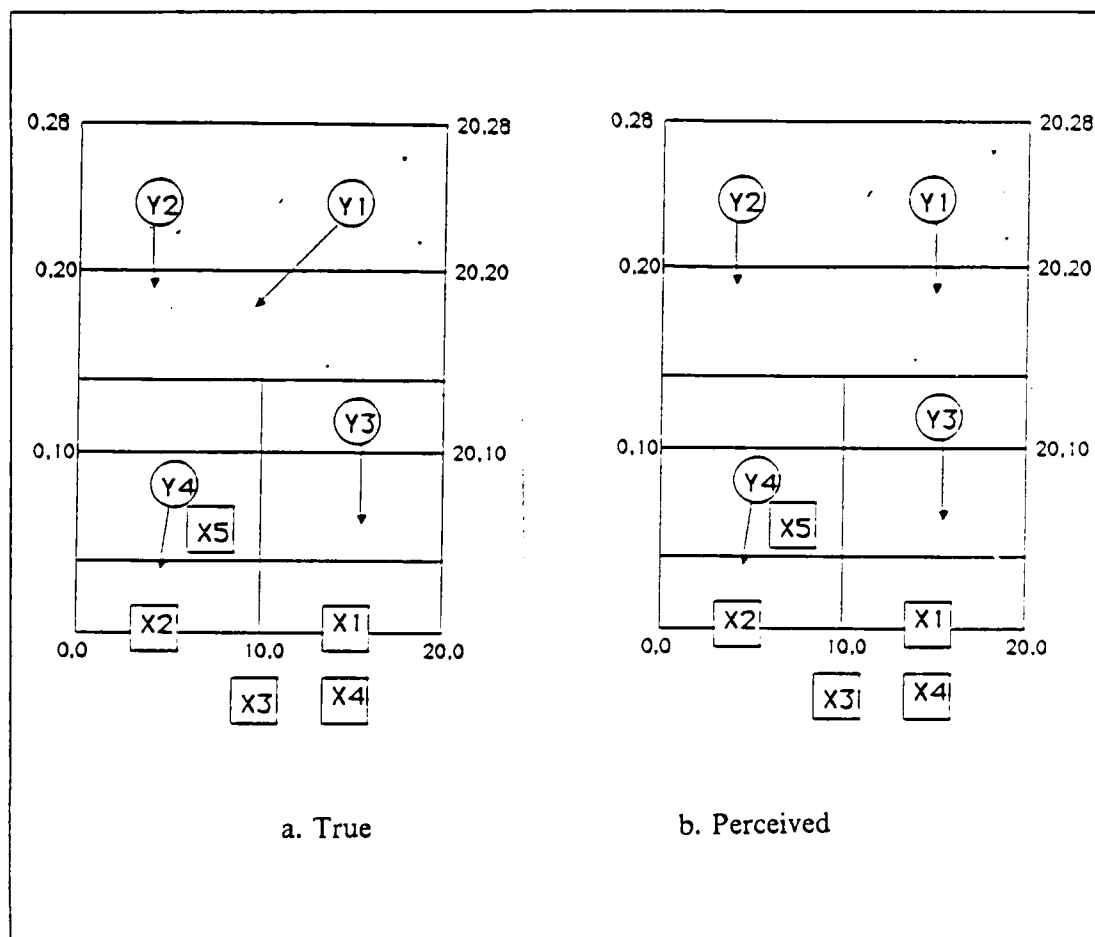
Figure 6.9   Situation at t = 3.

increased but is below that of the Blue forces defending in that sector. In sector 2 the Red forces are still projected to hold a slight advantage. This advantage does not warrant the commitment of the reserve battalion, X3.

6. **Situation at t = 4**

The position of the forces at time, t = 4, is shown in Figure 6.11a. Red Regiments Y1 and Y2 have entered the area of interest for sector 2 and are moving to support Y4 which continues to attack in that sector. Red Regiment Y3 has entered the area of influence for sector 1 and has been engaged by X1. X5 still attacks Y4 with
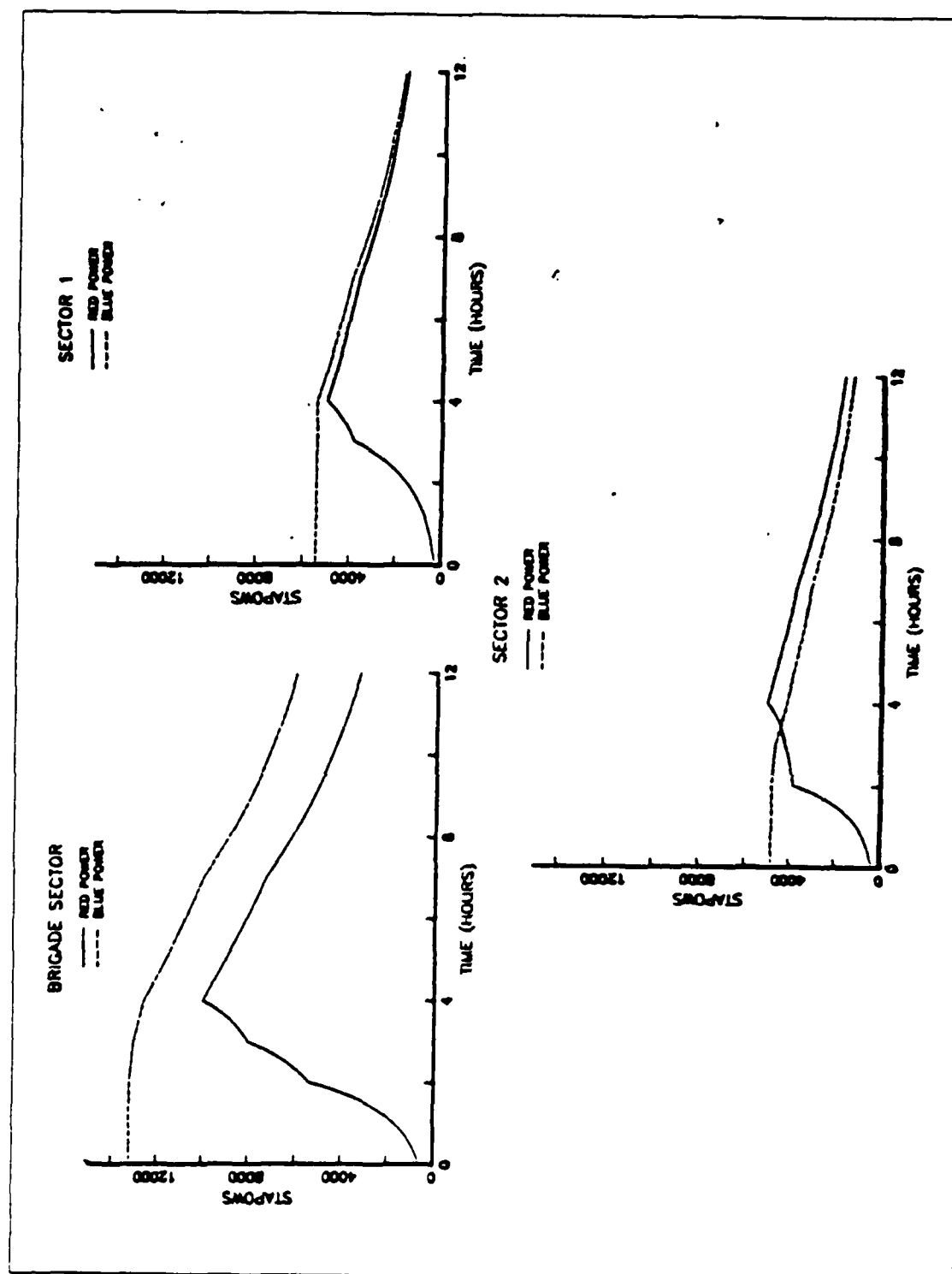
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Figure 6.10   Perceived Power Curves for t = 3.

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artillery fire while X4 continues to engage Y3. The Blue Brigade's CIP has received the following information vectors from the Execution Module:

$$(Y1,M,80,A,10,13)$$
$$(Y2,M,80,A,05,12)$$
$$(Y3,M,90,A,15,07)$$
$$(Y4,T,90,A,05,07) \, .$$
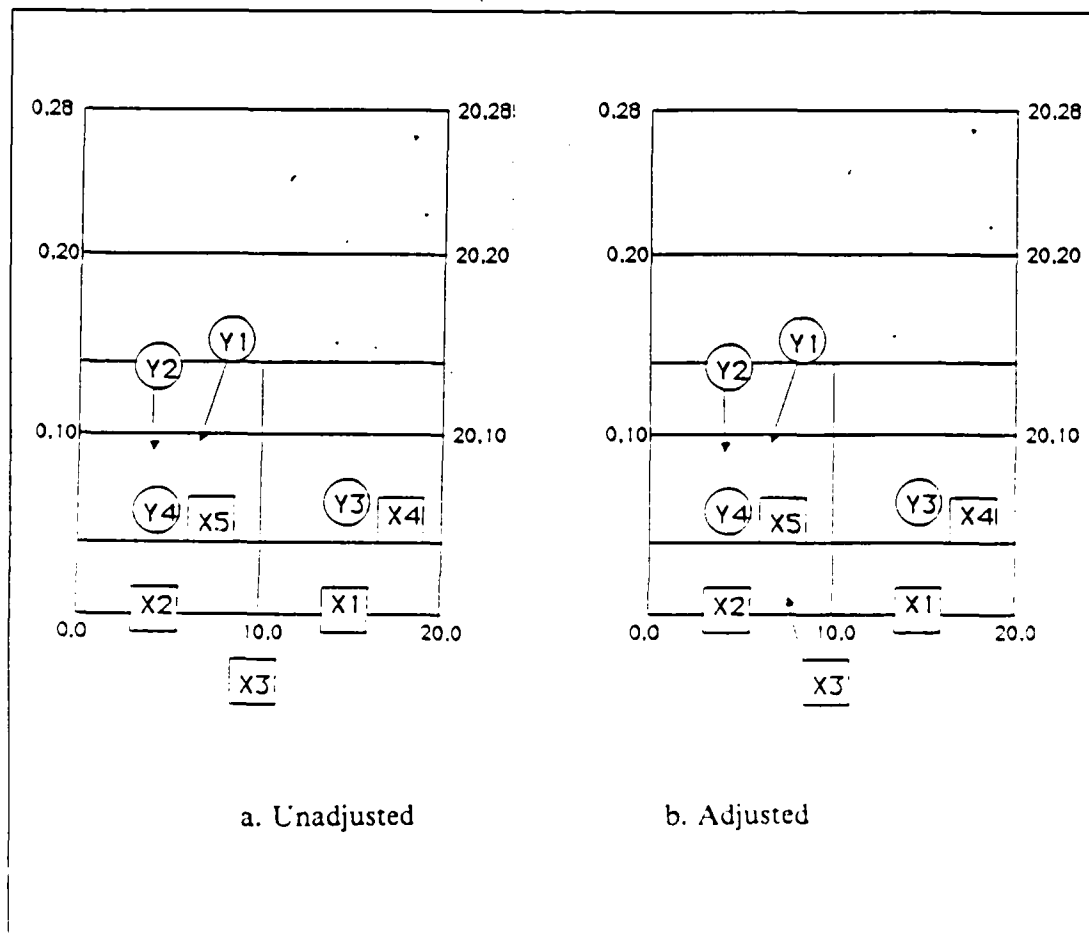

a. Unadjusted   b. Adjusted

Figure 6.11   Situation at t = 4.

The CIP conducts the target aggregation tests which results in the following intermediate target vectors:

$$(Y1,1,M,80,*,A,10,13)$$
$$(Y2,2,M,80,*,A,05,12)$$
$$(Y4,3,T,90,*,A,05,07)$$

(Y3,4,M,90,*,A,15,07) .

The IEP now estimates that the main attack will come in sector 2 and will consist of Red Regiments Y1,Y2 and Y4. The attack by Y3 will be a supporting attack designed to prevent X1 from maneuvering to assist in sector 2 and to siphon off potential Blue reserves. The IEP adjusted target vectors are:

(Y1,1,M,80,2400,M,03,07)

(Y2,2,M,80,2400,M,07,07)

(Y4,3,T,90,3300,A,05,07)

(Y3,4,M,90,2700,A,15,07).

The subordinate battalion CIPs are sent the adjusted combat information for their respective sectors. The Blue Brigade's perception of the battlefield mirrors the true situation for the first time during the battle.

The SIP curves for t = 4 are shown in Figure 6.12. It is apparent that the Blue Brigade still has more power than the combined Red forces in the Brigade's sector. However, the Red forces committed to sector 2 possess significantly more power than the Blue forces defending it. Without adjustments to the Blue plan the Red forces will be able to achieve a break-through in sector 2.

The Planning Module commits the reserve battalion, X3, to sector 2 . Additionally X4 is ordered to support sector 2 by continuing to attack Y1. The modified battlefield situation is shown in Figure 6.11b and the adjusted SIP curves sector for this modified plan are displayed in Figure 6.13. Now the power of the Blue Brigade has been alined so that it is superior to the Red power in both sectors. Based on these projected power curves the Blue Brigade will be able to prevent the Red forces from penetrating past the Brigade's rear boundary and therefore successfully complete its mission.

C.   SUMMARY

This example demonstrates the inter-relationships between the Execution, Intelligence and Planning Modules of ALARM. The key point for the decisioning making process in the Planning Module and the estimation procedure in the IEP sub-module of the Intelligence Module is that both the processes are both based on the perceived situation

The only information which comes from the Execution Module is ground truth. Error in the process can be first introduced in the CIP sub-module. An incorrect decision to
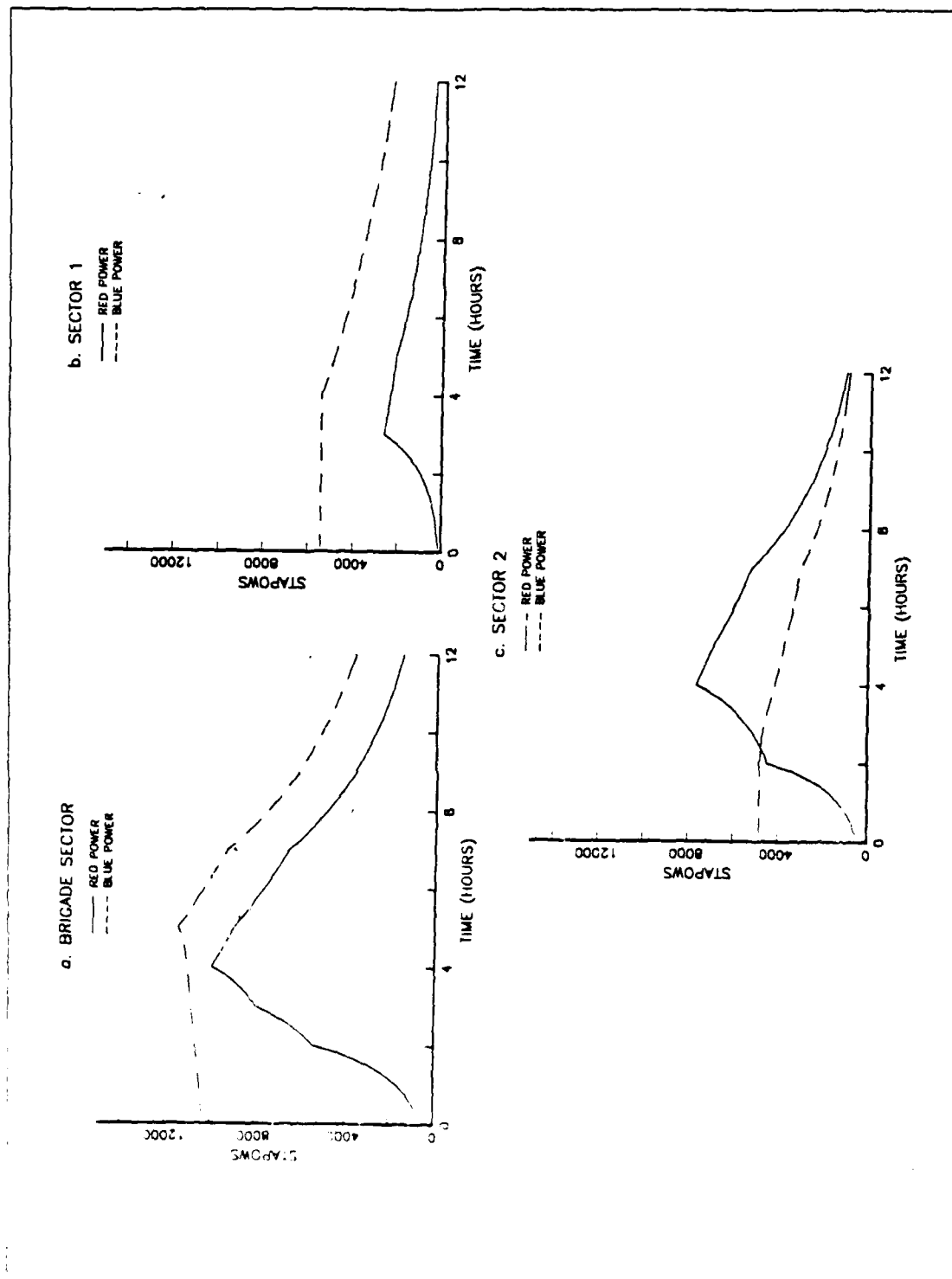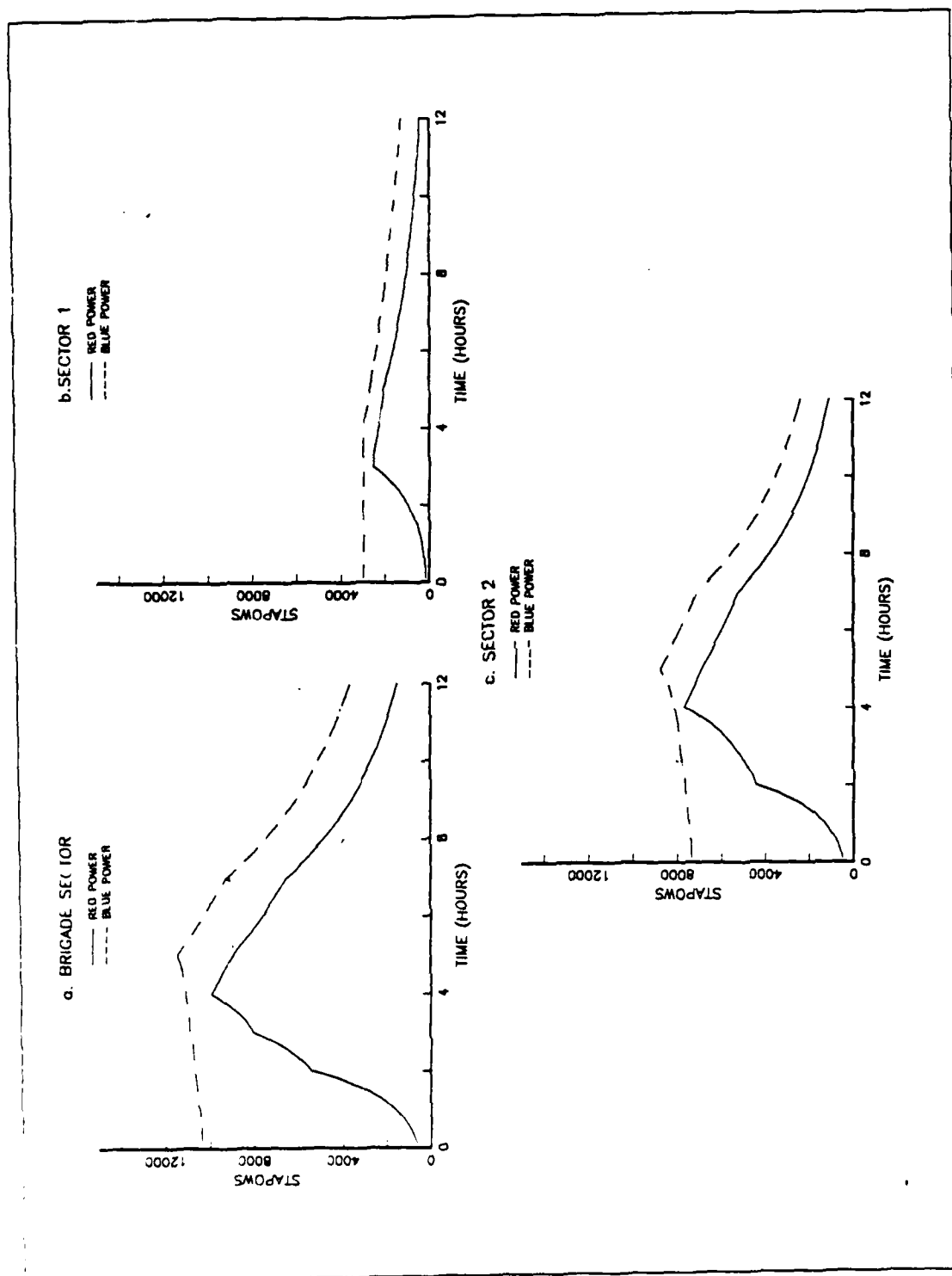
Figure 6.12 Perceived Power Curves for t = 4.

Figure 6.13 Adjusted Perceived Power Curves for t = 4.

either aggregate or not aggregate target vectors can result in the perception of the battlefield being distorted from ground truth. Since the intelligence estimate prepared by the IEP uses the target vectors this can result in an incorrect prediction of the enemy courses of action. The plans prepared by the Planning Module, which are in turn based on the intelligence estimate, may then be faulty and fail to correctly assign combat assets to cope with the enemy situation.

Subsequent information from the Execution module, as well as intelligence from senior units and combat information will tend to act as a correcting influence on the perceived state of the battlefield. The relationships between the modules can therefore be viewed as dynamic and self-correcting. As more reliable information is made available to the IEP the perceived state of the battlefield should approach ground truth.

VII. SUMMARY/FUTURE DIRECTIONS

A. SUMMARY

This thesis has developed the conceptual foundation for the Intelligence Module of the AIRLAND RESEARCH MODEL (ALARM). The relationship between the Execution, Planning and Intelligence Modules has been detailed. Methodologies by which the Intelligence Module can accomplish required functions were explored. The following are the key results.

- The Intelligence Module will consist of two sub-modules; the Combat Information Processor (CIP) and the Intelligence Estimate Processor (IEP).

- Information from the Execution Module will be routed to the appropriate CIP based on task-force hierarchy.

- The CIP receives raw information from the Execution Module and using the algorithms developed in Chapter III produces combat information. This combat information forms the basis for the intelligence estimate and subsequent plans developed by the Planning Module.

- The IEP will be tasked with developing an intelligence estimate. Specific functions of the IEP include matching targets to specific organizations in the enemy's order of battle, predicting the enemy's course of action and preparing the SIP curves for the enemy forces.

- Decisions will be based on the predicted future state of the enemy forces.

- The Execution Module will produce "ground truth" information, there is no built-in error. Deviations from ground truth arise because of the decision algorithms used by the IEP and CIP sub-modules.

- Target acquisition, which is a function of the Execution Module, could possibly be successfully modelled using a Lanchester-type formulation. The formulation must include components for acquisition as well as the loss of acquisition.

- The coefficients for a Lanchester-type formulation of acquisition could be obtained by a maximum likelihood estimation procedure. The output of high resolution combat simulations or field trials would be required for the estimation procedure.

In summary, the concept of the Intelligence Module developed in this thesis provides a basis for future research and study. The development of decision algorithms for the IEP are dependent on current ongoing projects. The successful completion of the terrain and avenue of approach models will open the way for future development of the intelligence estimation process. The required CIP functions are well identified. This thesis represents only the initial effort in identifying methodologies to accomplish the required tasks. Finally, Lanchesterian models of acquisition appear to hold great promise for modeling acquisition in ALARM.

B. FUTURE DIRECTIONS

There are several areas which require future research for the continued development of the Intelligence Module. The use of decision templates in the preparation of intelligence estimates needs to be fully explored. The current use of these templates by intelligence officers is a widespread and accepted practice. They provide a convenient starting point for developing decision algorithms to identify enemy organizations and predict their courses of action.

The successful use of a Lanchester-type formulation of acquisition is dependent upon developing estimates for the process coefficients. This will require either modifying an existing high resolution combat simulation or creating a new one for the specific purpose of obtaining times between acquisitions. In order to be applicable to a wide variety of situations several terrain and force mix scenarios should be explored. A data base to draw upon must be developed.

Finally, the algorithms used in the CIP must be selected, either from those presented in this thesis or developed else where. These algorithms should be converted to computer code and the initial steps of integrating them into ALARM accomplished

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